MODELING, DESIGN, AND TESTS OF POST-TENSIONED GLASS T-BEAMS

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MODELING, DESIGN, AND TESTS OF POST-TENSIONED GLASS T-BEAMS

submitted by **EMRULLAH KOCA** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** ________________

Prof. Dr. Ahmet Türer
Head of Department, **Civil Engineering** ________________

Prof. Dr. Ahmet Türer
Supervisor, **Civil Engineering, METU** ________________

Examining Committee Members:

Assoc. Prof. Dr. Uğur Polat
Civil Eng.Dept., METU ________________

Prof. Dr. Ahmet Türer
Civil Engineering, METU ________________

Prof. Dr. Erdem Canbay
Civil Eng.Dept., METU ________________

Assoc. Prof. Dr. Eray Baran
Civil Eng.Dept., METU ________________

Assist. Prof. Dr. Alper Aldemir
Civil Eng.Dept., Hacettepe University ________________

Date: 31.01.2019

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Emrullah Koca

Signature:

ABSTRACT

MODELING, DESIGN, AND TESTS OF POST-TENSIONED GLASS T-BEAMS

Koca, Emrullah
Master of Science, Civil Engineering
Supervisor: Prof. Dr. Ahmet Türer

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Traditionally, glass is widely used in buildings as windows where its brittleness and strength capacity are not significant. Although there is more demand for usage of glass as a structural material, common fear of its brittle nature has mostly hindered its structural use. Aesthetics, recyclability, and transparency are the main reasons of the interest for glass in structural field. Moreover, glass shows significantly more benefits for certain types of projects such as existing building extensions and historic building preservation, where envelopments with minimal visual interruption are needed. However, more research should be done to be able to meet the demands and benefit from the advantages of glass. This thesis aims to enhance the use of glass as a structural material, so a T-shaped glass beam is studied to develop a proper and safe design. Since glass is a brittle material and has high compressive strength and lower tensile strength, a T-beam is post-tensioned in order to increase its initial fracture capacity and obtain ductile post-fracture performance. In this study, several material tests are conducted to confirm the theoretical mechanical properties of glass as a material under compression and bending (indirect tension). After obtaining mechanical properties of the glass to be used in research, Finite Element Models (FEMs) of the T-beams were generated and analytical hand calculations were done for the same types of glass beams. The tests of T-shaped annealed (float) and tempered (toughened) glass beams with and without post-tensioning were conducted. The results of the experiments were compared with the analytical hand calculations and FEMs. Excel based computation sheets for design process and tables for quick and simple guide were also generated within the scope of this study.

Keywords: Post-tensioned Glass Beam, Glass as a Structural Material, Post-tensioning, Glass Beam

ÖZ

ARDGERMELİ T-KESİTLİ KİRİŞLERİN MODELLENMESİ, TASARIMI VE DENEYLERİ

Koca, Emrullah
Yüksek Lisans, İnşaat Mühendisliği
Tez Danışmanı: Prof. Dr. Ahmet Türer

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Cam, genel olarak kırılganlığının ve mukavemet kapasitesinin çok önemli olmadığı, binaların pencerelerinde kullanılır. Camın yapısal bir malzeme olarak kullanımına ilişkin talebin çok olmasına rağmen, kırılganlığından kaynaklanan korku yapısal olarak kullanımını engellemiştir. Estetik, geri dönüştürülebilirlik ve saydam oluşu camın yapısal alandaki talebin temel nedenidir. Ayrıca, cam, görsel kesintinin minimum olması gereken mevcut binaların uzatılması ile tarihi yapıların restorasyonu gibi projelerde oldukça kullanışlı bir malzemedir. Bununla birlikte, taleplerin karşılanabilmesi ve camın avantajlarından yararlanabilmek için cam hakkında daha fazla araştırma yapılmalıdır. Bu tez, camın yapısal bir malzeme olarak kullanımını arttırmayı hedeflediğinden, uygun ve güvenli bir tasarım geliştirmek için T-kesitli bir cam kiriş üzerinde çalışılmıştır. Cam, yüksek basınç mukavemeti ile düşük çekme mukavemetine sahip ve kırılgan bir malzeme olduğundan, T-kesitli kirişe, başlangıç kırılma kapasitesini arttırmak ve sünek bir davranış elde edebilmek için ardgerme uygulanmıştır. Bu çalışmada, camın teorik mekanik özelliklerini doğrulamak amacıyla çeşitli camlardan, basınç ve eğilme testleri gerçekleştirilmiştir. Çalışmalarda kullanılacak camın mekanik özellikleri tespit edildikten sonra, T-kesitli camların sonlu elemanlar modelleri tasarlanmış ve aynı boyuttaki kirişlerin el hesapları yapılmıştır. Ardgermeli ve ardgermesiz T-kesitli düz ve temperli cam kirişlerin deneyleri gerçekleştirilmiş, sonuçlar el hesapları ve analitik modeller ile karşılaştırılmıştır. Bu çalışma kapsamında, tasarım süreci için Excel tabanlı hesaplama sayfaları ile hızlı ve basit kılavuz tabloları oluşturulmuştur.

Anahtar Kelimeler: Ardgermeli Cam Kiriş, Yapısal Cam, Ardgerme, Cam Kiriş

To My Family

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First of all, I would like to thank my supervisor Prof. Dr. Ahmet Türer not only for his support and guide through this study but also his being polite to me under any circumstances. It was a great opportunity to work with him.

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A	Area
b	Cross-sectional width
DL	Dead load
E	Modulus of elasticity
$E_{characteristic}$	Characteristic modulus of elasticity
E_{mean}	Average modulus of elasticity
F	Force
f	Eccentricity for post-tensioned wire rope
f_{cjk}	Characteristic compressive strength during transfer case
f_{ck}	Characteristic compressive strength
$F_{fracture}$	Fracture force
FL	Final load
f_u	Ultimate strength of wire rope
G	Shear modulus
h	Cross-sectional height
I	Moment of inertia
ℓ	Sample length
LL	Live load
M	Moment
M_{max}	Maximum moment
P	Load
P_{crack}	Crack load
P_{design}	Design load
P_{max}	Maximum load
PR	Pre-stressed
PT	Post-tensioning
$Q_{glue\ point}$	First moment of area relative to glue point

$Q_{neutral\ axis}$	First moment of area relative to neutral axis
R	Reaction force
SD	Standard deviation
t	Thickness
V	Shear force
V_{max}	Maximum shear force
$\bar{y}$	Neutral axis
α_T	Coefficient of thermal expansion
δ_{final}	Deflection at final case
δ_{max}	Maximum deflection
$\delta_{max,mean}$	Average maximum deflection
$\delta_{transfer}$	Deflection at transfer case
ε	Emmisivity
$Ø_{wire}$	Diameter of wire rope
ν	Poisson ratio
λ	Thermal conductivity
ρ	Density
σ	Stress
σ_{bottom}	Mid-span stress at bottom of the beam
σ_{ck}	Characteristic compressive strength
$\sigma_{compressive}$	Compressive strength
σ_{ctk}	Characteristic tensile strength
σ_{mean}	Average stress
σ_{top}	Mid-span stress at top of the beam
$\tau_{glue\ point}$	Shear stress at glue point of the beam
$\tau_{neutral\ axis}$	Shear stress at neutral axis of the beam
ΔM_{final}	Resultant moment at final case
$\Delta M_{transfer}$	Resultant moment at transfer case
ΔV_{final}	Resultant shear force at final case
$\Delta V_{transfer}$	Resultant shear force at transfer case

CHAPTER 1

INTRODUCTION

In the first chapter, a brief history about glass, its types and properties as well as post-tensioning application are introduced. Moreover, literature review carried out is declared and the objectives and scope of the thesis are provided.

1.1. Glass as a Material

Glass is an inorganic, visco-elastic, and isotropic material which has a non-crystalline molecular structure. The typical composition of glass consists of silica-SiO_2 (70-74%), lime-CaO (5-12%), soda-Na_2O (12-16%) and other chemical elements with influence to transmittance, thermal properties, tensile strength, fracture toughness, and color etc. Glass is a transparent material which is solid at room temperature and starts to melt at about 600°C but liquefies completely at 1450°C to 1600°C depending on the composition of glass. When compared with steel, steel begins to soften at about 425°C and loses about half of its strength at 650°C. Glass material is a good thermal and electrical insulator; it can be poured, blown, and molded into plenty of shapes. At ordinary temperatures, glass materials are relatively strong, chemically and biologically inactive, and corrosion resistant. Considered as a structural material, no plastic deformation occurs before the failure and it breaks suddenly unlike steel and aluminum where plastic mechanism can be formed. Glass has a high compressive strength and a weaker tensile strength. Stress or moment re-distribution does not occur in glass, local and then global failure is very common in glass. On the other hand, glass is almost ten times stronger in compression compared to tension, so the breakage of a glass beam mostly happens due to its tension limit. That’s why, a glass beam may be combined/supported with a material that is strong in tension in order to prevent the immediate breakage and make it useable as a structural material.

1.2. History of Glass

In prehistoric times, glass naturally occurred near volcanic regions and formed after lightning strikes on sand. Glass manufacturing has an old-age tradition which dates back to around 3500 BC when glass is believed to have been first artificially produced in Egypt and Mesopotamia to be used as jewelry and vessels. Since then the applications of glass has increased by industrial processes. Glass buildings, primarily, were used in cities at the beginning of 20th century. Glass construction has become the symbol of development in many countries, where people tend to see these buildings as symbols of affluence and luxury. Glass is all around us nowadays and continues to offer structural solutions, either in itself or used in combination with other materials, a trend which is very likely to continue in the future. In 1958 Pilkington and Bickerstaff introduced the revolutionary float glass process to the world. This method gave the sheet uniform thickness and very flat surfaces. Nowadays, as architects begin to ask for more structural glass in their projects, engineering and manufacturing of glass has been developed significantly by today's high-technology. The aesthetic result of glass as a structural member may be a totally transparent structure. One of the first examples of glass material as a structure is the Fagus factory by Walter Gropius of the Bauhaus group in 1926 (Figure 1). In this example, glass is not a structural load carrying member but mainly used as exterior covering. The structural usage of glass has many examples as well; for instance, Apple Store Building in New York (Figure 2) is a good example where glass is used to carry building load. Glass can be connected to almost all kinds of architectural elements, such as steel, masonry walls, and concrete. Glass beams are mostly used to support clear glass panes because of its transparency and other issues.

Figure 1: Fagus Factory of the Bauhaus, Germany[1]

Figure 2: Apple Store Building, Upper West Side, New York [2]

[1] http://moonlightspostcardblog.blogspot.com/2011/11/germany-fagus-factory-in-alfeld.html
[2] http://www.mackloweproperties.com/pastProjects/projects-AppleBuilding.html

Arab Urban Development Institute Reading Room in Riyadh is also a beautiful example of glass usage as structural load carrying members (Figure 3). The connections using L shaped metals and fasteners is a good example on how structural glass members can be connected.

Figure 3: Arab Urban Development Institute Reading Room, Riyadh [3]

1.3. Production Process and Types of Glass

In 1958, Pilkington and Bickerstaff introduced the revolutionary float glass process to the world. This method gave the sheet uniform thickness and very flat surfaces, so manufacturing glass has become a common industry. Traditionally glass was made by blowing liquid glass derived by melting sand calcium oxide and sodium carbonate to extremely high temperatures and cooling the liquid to the desired shape. Its properties can be identified by adding certain admixtures to the raw materials or by providing suitable cover to meet different needs such as coloring the glass. In Pilkington Process (Figure 4); large quantities of raw materials (clear sand, calcium oxide and sodium carbonate) are mixed in desired proportion in a glass production plant. Certain admixtures are added to the plant in order to identify the properties of glass. The

[3] http://www.glasslimited.com/portfolio-item/glass-cube-reading-room

mixture is then heated in a gas fired furnace or electric smelter, pot furnace or kiln. Quartz sand without additives becomes glass at a temperature of 2300^{o}C, adding sodium carbonate (soda) reduces the temperature needed to produce glass to 1500^{o}C. A homogeneous mixture of molten glass is then formed. This mixture is then floated on a molten tin to form glass of desired thickness. The way in which the glass is cooled determines its strength. For example, tempered glass is produced by cooling the glass in a rapid rate. It has to be cooled after protecting a suitable temperature i.e. it has to be annealed. Glass making is an energy extensive process, so it requires high amount of energy.

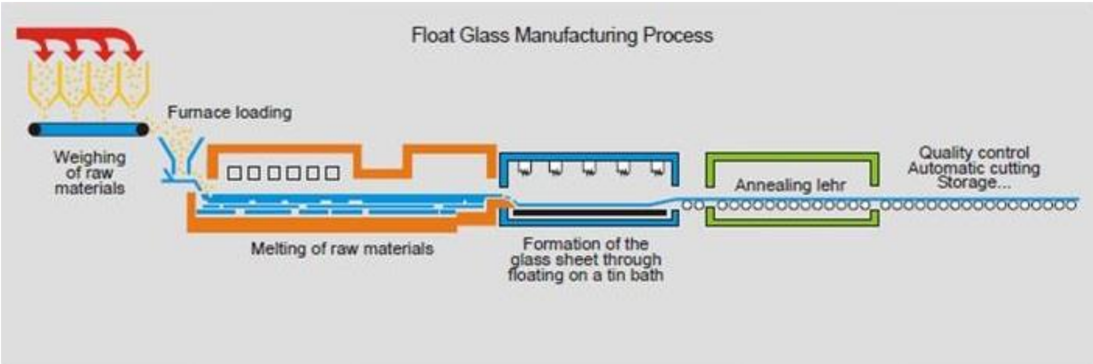

Figure 4: Pilkington Process [4]

There are several types of glass such as fully tempered, heat strengthened, float, laminated, and insulated.

Fully Tempered Glass: It is also called toughened glass. After heating float glass, it is cooled rapidly by cold air jets. The aim of the tempering process is to create a residual stress field in the thickness direction that has tensile stresses in the core and compressive stresses at the surfaces of the glass (Figure 5). This result is done by fast cooling process. If the glass is subjected to loads, cracks will not grow unless there is a net tensile stress field at the surface of the glass. Fully tempered glass usually breaks into small harmless pieces (Figure 6).

[4] http://www.frontdesk.co.in/glass.html#.W27Afs4zaUk

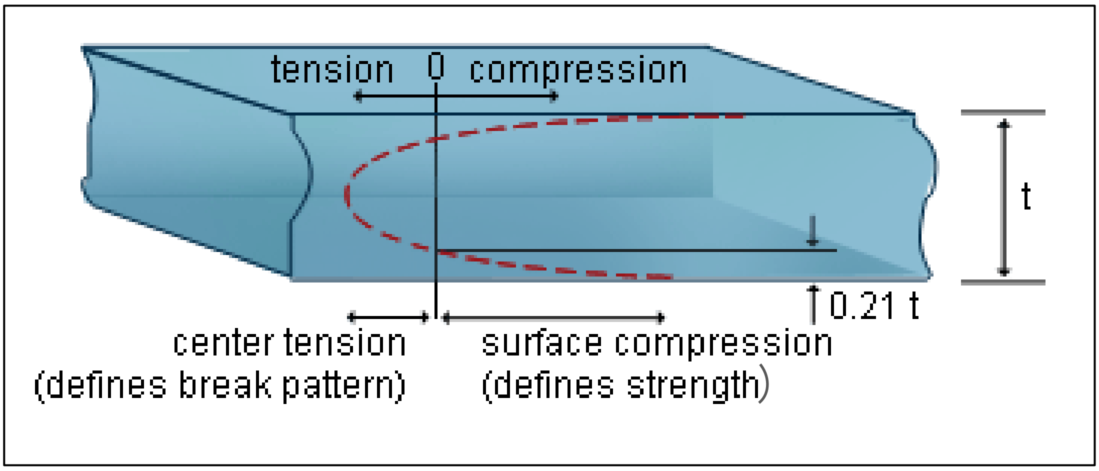

Figure 5: Stress distribution in a tempered glass section[5].

Heat Strengthened Glass: Heat strengthened glass is produced similarly as fully tempered glass, but the cooling rate is lower. The resulting residual stress is lower, and thus the tensile strength is lower than of fully tempered glass. At fracture, the fragments are larger than tempered glass but smaller than float glass.

Float Glass: It is also called soda lime glass, annealed glass or clear glass. Float glass is produced by annealing the molten glass on a bed of molten metal[6] (Usually molten tin). It is produced by slowly cooling glass to avoid internal stresses. Float glass is the most widely used glass type and is used in making canopies, shop fronts, glass blocks, and railing partitions etc. Float glass can be manufactured in 3, 4, 5, 6, 7, 8, 10, 12, 15, 19, 25 mm thicknesses and maximum in 6.0 x 3.2 m sizes. At breakage, float glass splits into large fragments (Figure 6).

Laminated Glass: Laminated glass consists of two or more glass panes bonded by an interlayer. The glass panes can have different thicknesses and heat treatments. Laminated glass is used in architectural glazing for two reasons. Firstly, if one glass pane breaks, the remaining pane(s) can continue to carry the applied loads. Secondly, the scattered glass pieces can stick to the interlayer and serve to prevent people from getting injured (Figure 6). The interlayer is most often made of polyvinylbutyral

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[5] http://www.glazette.com/Glass-Knowledge-Bank-25/tempered-glass.html
[6] https://www.youtube.com/watch?v=JMGkbrETU8M

(PVB). The nominal thickness of a single foil of PVB is 0.38 mm. two (0.76 mm) or four (1.52 mm) foils form one PVB interlayer. PVB is a viscoelastic material and the physical properties depend on temperature and load duration. PVB behaves nonlinearly when subjected to large deformations, but can be treated as a linear elastic material when subjected to small deformations. Beside PVB interlayer materials are Ethylene Vinyl Acetate (EVA), SentryGlas (SGP) etc.

Figure 6: Typical fracture shape of float, tempered and laminated glass[7]

Insulated Glass: An insulated glass consists of two or more glass panes with intermediate gas space(s). Insulated glasses are mostly used for their thermal insulation properties. The gas space is sealed and then it is filled with dehydrated air or another gas such as krypton, argon, or xenon. The glass panes are connected using a spacer and a sealant. It is possible to use all types of glasses in an insulated type, for example float and laminated glasses in insulated glass.

1.4. Properties of Glass

The more transparency buildings have, the more they utilize natural energy, but opaque structural elements block a huge amount of natural light and view. As cullet (waste glass that is crushed to be melted to form new glass) is an essential ingredient

[7] https://www.cardinalcorp.com/products/laminated-glass/

in the manufacture of float glass, it is possible that glass application could produce zero waste and needs minimal energy over its life cycle. Some physical properties of glass are mentioned below one by one.

Transparency: This property allows visual connection with the outside world and provides more energy utilization. Transparency can be permanently changed by adding admixtures while producing glass.

U-value: The U-value is the measure of how much heat is transferred through the glass. If the U-value is lower, it means that the glass has a better insulation property. The U-value can be decreased by some types of insulated glass.

Greenhouse effect: The greenhouse effect refers to circumstances where the short wavelengths of visible light from the sun pass through glass and are absorbed, but longer infrared re-radiation from the heated objects are unable to pass through the glass. This effect leads to more heating and a higher resultant temperature which means energy saving as well. However, energy saving from this effect depends on the climate and location of the structure built.

Workability: Glass is capable of being worked in many ways. It can be blown, drawn or pressed.

Recyclability: Glass is 100% recyclable; culets are used as raw materials in glass manufacture. This could produce zero waste which is a much more preferable compared with some other structural materials e.g. concrete.

Visible transmittance: Visible transmittance is the fraction of visible light that comes through the glass.

Energy efficiency and acoustic control: Energy-efficient glazing is the term used to describe the double glazing or triple glazing use in windows. Unlike the original single glazing or old double glazing, energy-efficient glazing incorporates coated glass to prevent heat escaping through the windows. The air barrier also enhances acoustic control.

Insulation: Glass is an excellent insulator against heat, electricity and electromagnetic radiation. It has a good insulating response against visible light transmission. Certain special type of glass has high resistance against ultra-violet, infrared and x-ray transmission. It has an excellent resistance against sound transmission if it is used in proper thickness.

Chemical Resistance: Glass can withstand the effect of the chemical reaction under different environmental conditions or acidic effects. It has excellent resistance to most chemicals, including solutions of inorganic alkalis and acids, such as sulfuric acid and ammonia.

Color and Shape Varieties: Glass can be blown, drawn and pressed to any color, shape, and varieties. Nowadays so many color and shape varieties are available in the market depending upon their use, dimensional and safety requirements.

Some physical properties are explained. However considering glass as a structural material, mechanical properties such as strength capacity may be more important.

Strength: Glass is a brittle material but certain laminates and admixtures can increase its modulus of rupture. The strength of glass depends on manufacturing process and types of material contents, surface condition and edge quality, environmental condition, stress distribution on the surface, size of the stressed area, and damage of glass surface.

Some mechanical and physical properties of glass are shown in Table 1.

Table 1: Mechanical and Physical Properties of Glass

Glass Property	Value	Unit
Density (ρ)	2500	kg/m^3
Modulus of elasticity (E)	70	GPa
Shear modulus (G)	30	GPa
Poisson's ratio (ν)	0.23	-
Coefficient of thermal expansion (α_T)	$9*10^{-6}$	K^{-1}
Thermal conductivity (λ)	1	W/(mK)
Emissivity (ε)	0.89	-
Tensile strength (σ_{ctk}) (Float Glass)	40-50	MPa
Tensile strength (σ_{ctk}) (Tempered Glass)	120	MPa
Compressive strength (σ_{ck})	400-800	MPa

Typical stress-strain curves of structural materials such as glass, concrete, steel and timber are displayed in Figure 7. It should be noted that the graphs are not scaled. It can be inferred from the graphs that glass is the most brittle material among the materials compared. However, it should be pointed that tensile strength value of glass is much higher than tensile strength value of concrete.

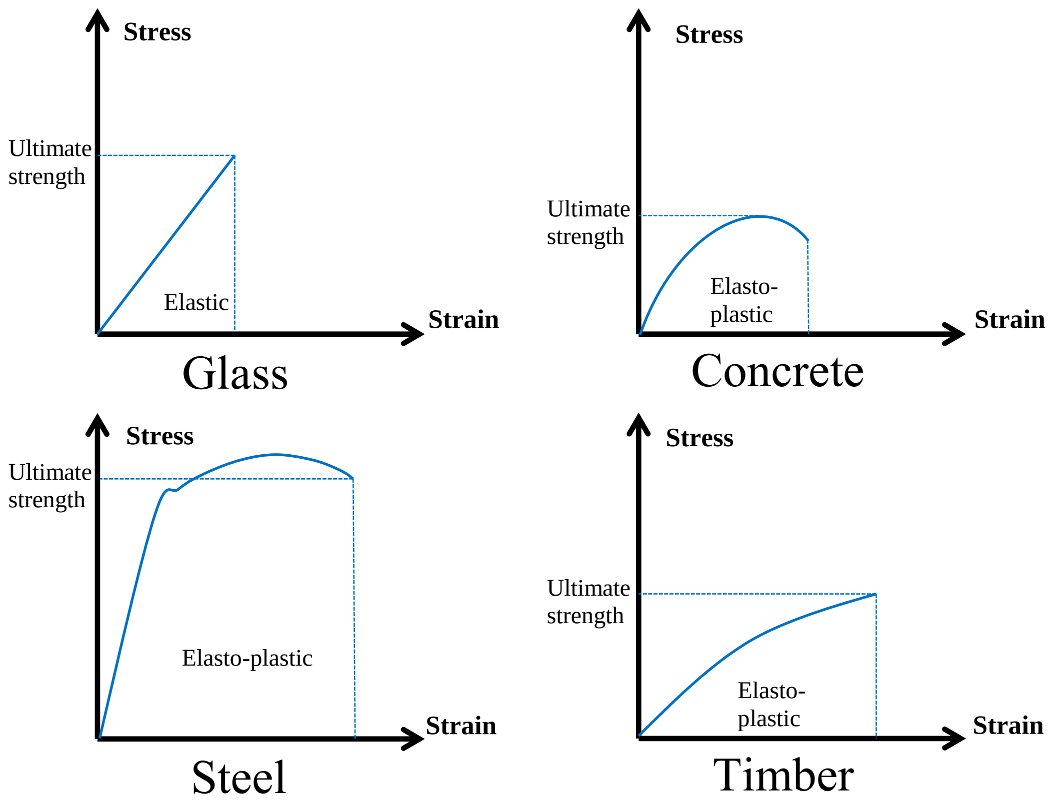


Figure 7: Typical stress – strain graphs of glass, concrete, steel, and timber under bending (indirect tension)

1.5. Post-Tensioning Application

Pre-stressing can be applied to members in two ways, by pre-tensioning or post-tensioning. In pre-tensioned members the pre-stressing strands are tensioned against restraining before the material is cast and then it is allowed to harden. After it gains sufficient strength, the strands are released and their force is transferred to the member. Pre-stressing by post-tensioning involves installing and stressing pre-stressing strand or bar tendons after the material has been placed, hardened and attained a minimum compressive strength for that transfer. The typical stress-strain behavior of glass is similar to concrete while tensile strength of glass is about 10% of its compressive strength. Plain glass members are likely to crack in the tensile zone when loaded. Reinforcing the tensile zone of a beam helps the beam to resist tensile forces after being cracked. However, post-tensioning the tensile zone compresses very fine cracks and reduces or eliminates cracking. The resulting post-tensioned glass member may crack, but it can effectively carry more loads with a ductile failure. However, post-tensioned members should be designed for non-crack cases. The function of post-tensioning is to remain the structure under compression in those regions where load causes tensile stress. Tension caused by applied loads will first have to cancel the compression induced by the post-tensioning before it can crack the glass. By placing the post-tensioning in the simple-span beam, compression and negative moment is formed in the member, creating upward deflection. The magnitude of post tensioning force and dimensioning is about the design part. The components of post-tensioning system consist of pre-stressing steel, anchorages, and post-tensioned members. Wires, strands or bars can be used to post tension the members. Anchorage is a special bearing plate or anchorage device that transfers tendon force into the material but does not meet normal analytical design requirements for basic bearing plates. These anchorages typically require increased confinement reinforcement and should be accepted on the basis of physical tests. There are short term (immediate) and long term (time dependent) losses in the post tensioning systems. Elastic shortening, slip at anchorages immediately after pre-stressing, friction between tendon and tendon duct are the immediate losses for materials. The time dependent losses are relaxation of pre-stressing steel, creep and shrinkage losses for concrete. However, the losses for glass shall be studied and investigated. The strength capacity of the member can be increased by calculating the losses and designing post-tensioning.

Although field application of post-tensioned glass beams was not found in the literature, a few studies and lab tests were encountered. Advantages of post tensioning in glass beams can be considered as a) increase in cracking capacity, b) ductility gained by post cracking strength, c) no losses because of shrinkage, d) high strength of glass which is about 400 MPa in compression and about 40 MPa in tension, and appealing view of the transparent glass material.

Post-tensioning in glass might be complicated because of the viscous flow over extended periods of time and further studies might be necessary. Although glass flow can be a different form of creep; such behavior might be relatively less critical during the lifespan of a civil engineering structure.

1.6. Literature Review

Glass which could be used for architectural glazing is produced by the float process introduced by Pilkington Brothers (1950). In this period, glass has been used as a structural material with steel, timber, reinforcement, and post-tensioned steel. The main goals of post-tensioning a structural glass beam were explained as increasing the initial fracture strength of the glass and providing a significant post-fracture residual load-carrying capacity.

Reinforcing glass beams generates an internal moment capacity, which enables the fractured beam to still carry significant load. This concept is studied earlier by several researchers. (Kreher & Natterer, 2004; Cruz & Pequeno, 2008; Louter, Belis, Veer, & Lebet, 2012; Speranzini & Agnetti, 2014)

The concept of post-tensioned glass beams has currently been studied in a limited number of researches. Bos et al. (2004) prepared a 3 m long 1:4 scaled prototype box section glass beam, reinforced by two small stainless steel profiles. The prototype has been tested in a displacement controlled four-point bending test and they have observed that the safe behavior of glass structural elements is possible by adding a minimal amount of steel. They prepared again a 3 m long parabolic, pre-stressed (Ø =8 mm high strength steel) T-section beam in order to obtain a less sensitive section design, less weight and a higher load carrying capacity. Considering both of these tests, they observed that the failure of the box section started at a much lower stress level which means that the compressive stress in the upper zone of the beam was less and concluded that more compressive stress has to be built up in the upper zone of the beam before failure occurs.

Bos et al. (2004) tested a post-tensioned T-sectioned glass beam prototype (Figure 8). This beam was composed of 3 layers of segmented annealed glass. A curved stainless steel section has been integrated in the web of the beam. Through this hollow section a 7 mm diameter high strength steel tendon was fed and tensioned at the beam ends. From the results of this study it was concluded that the concept of post-tensioning an annealed glass beam is feasible and highly beneficial, however the explosive failure poses possible risks for building applications.

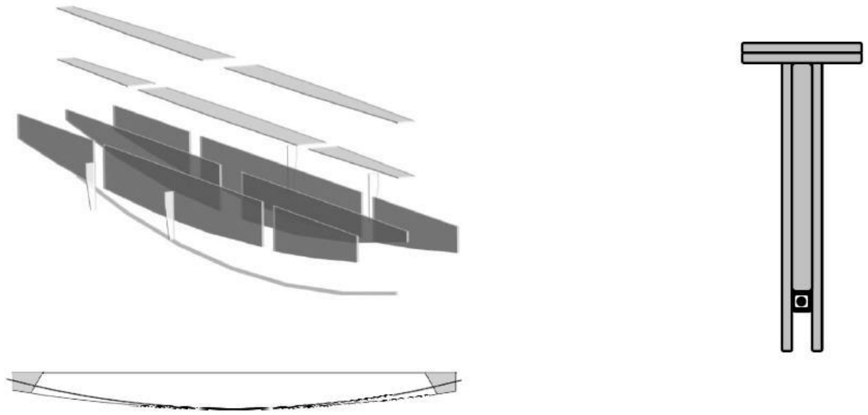


Figure 8: T-section beam layout (left) and cross section (right) (Bos et al, 2004)

Louter et al. (2006) investigated the transmission of the post tensioning forces to the glass beam ends. They developed four different methods for transferring post tensioning forces and tested them in compression tests. In two of the transmission methods, a steel end plate transferred the force directly to the edges of the beam ends. In the other two methods the force was transferred via aluminum wedges, which were bonded to the side planes of the glass beam. In this research, it was observed that the most essential aspect of post tensioning glass beams seems to be the alignment of the area which the post tensioning forces are transferred. Furthermore, misalignments and small setting errors were observed to be very critical in transmission of the post tensioning forces to the glass beams.

Belis et al. (2006) worked on the effect of post tensioning on the buckling behavior of a T- shaped glass beam. The conclusion was that the geometry of the prototype had a relatively good resistance to buckling and the beam failed due to fracture of the glass. In this study, the effect of shape imperfections and eccentricities were not examined. Cruz and Pequeno (2008) compared four types of beams which are timber, glass, composite I and rectangular beam. They tested two of each type with 3200 mm span length. After the tests, they concluded that silicone adhesive was the most advisable glue material because it allowed greater indication of flexibility. Also, in the composite system, timber provided ductility and glass offered resistance and stiffness. Louter (2013) tested different post-tensioned systems (Figure 9). From the results it was concluded that these post-tensioned beams are feasible concepts in which the residual load-carrying capacity increased significantly, as well as the initial failure strength. The advantage of the post-tensioned glass beams when compared to beam made only with annealed glass was shown in Figure 10.

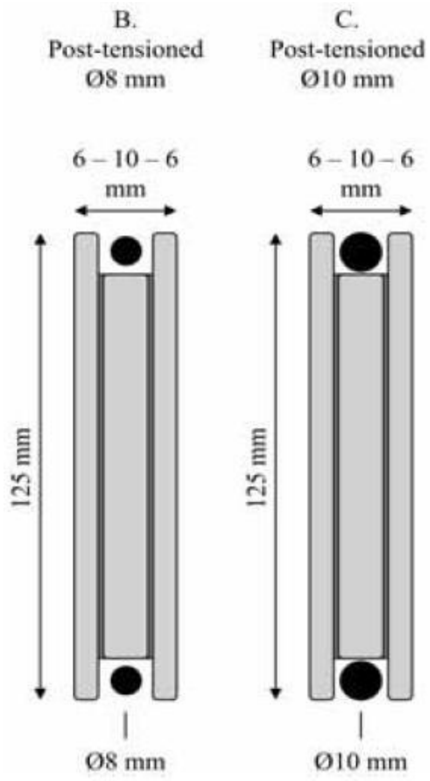


Figure 9: Post-tensioned beams tested by Louter. (Louter, 2013)

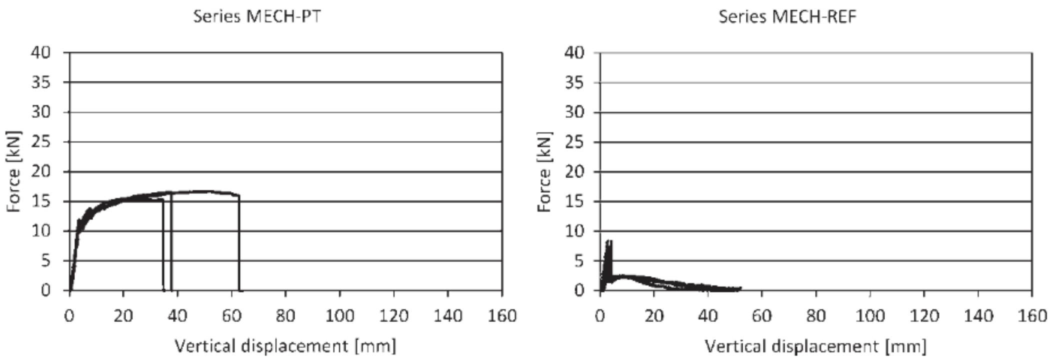


Fig. 8. Force-displacement curves of series MECH-PT, post-tensioned beams with unbonded M8 tendons.

Fig. 9. Force-displacement curves of series MECH-REF, reference beams without tendons.

Figure 10: Structural behavior of two glass beams. (Louter, 2013)

Louter et al. (2014) made some explotary experimental investigations on post tensioned structural glass beams. Their aim was to contribute to the knowledge on post tensioned glass beams and investigate the mechanical response of such system. This was done with four-point bending tests on 1500 mm long glass beam specimens. The specimens consisted of beams with mechanically anchored post-tensioning tendons integrated at the top and bottom edge of the glass beams, beams with pre-tensioned tendons adhesively bonded at the lower edge of the glass, and reference beams which are identical to the post-tensioned glass beams, but without post-tensioning tendons. It was concluded that post-tensioning structural glass beams, by means of mechanically anchored or adhesively bonded tendons, was a feasible concept which provided increased initial fracture strength and enhanced post-fracture performance.

Jordao et al. (2014) studied analytically a laminated glass beam reinforced with pre-stressed cables numerically (Figure 11). The purpose of this paper was to establish a finite element model of the beam in which a parametric study was done regarding the choice of the element, the mesh dimensions, the choice of the feature used to model the lamination. Then, benchmarking with experimental results and comparison was done to test the quality of the numerical model dealing with instability issues. The main conclusions for this thesis were that elements along the beam's height lead to the best compromise between accuracy and time.

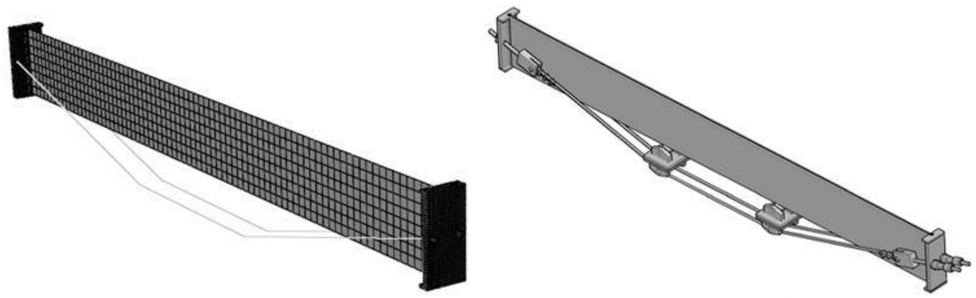


Figure 11: Laminated glass beam with prestressed cables (Jordão et al.,2014)

Engelmann and Weller (2016) studied the results of an experimental series of three 9 m glass beams with a 24 mm high-grade spiral cable tensioned up. The primary aim was to describe the load-bearing behavior of large-span, post-tensioned glass beams and to determine their ultimate load. The secondary aim was to present a practical application by designing a 9 m pedestrian bridge based on the beam design that was displayed at Glasstec 2014 in Düsseldorf, Germany. During the non-destructive tests with higher cable loads, the process was stopped manually when the lateral deflection increased exponentially. Furthermore, the post-tensioning resulted in a linear increase in the mean compressive stress at the bottom of the beam. It was concluded that an analytical evaluation in this stage remains usable for preliminary design. Consequently, an upscaling up to 9 m in span is feasible and confirms the results presented in the study.

1.7. Objective and Scope

Traditionally, glass is widely used in buildings as window glasses. Used in this way, glass is subjected only to transient wind loading and its self-weight conditions, where its brittle nature and strength capacity are not significant. Although glass is a beautiful material, common fears of its brittle nature and weakness have mostly restrained its structural use. That’s why it has only been some decades ago that glass has emerged as a structural building material. However, more research should be done to be able to increase the use of glass in construction area, which is one of the main aims of this study.

In this study, several tests were prepared and conducted to confirm the theoretical mechanical properties of glass as a material under compression and bending (indirect tension). After obtaining mechanical properties of the glass to be used in research, T-shaped annealed (also named as "float" or "regular glass") and tempered glass beams with and without post tensioning were tested and results were compared with analytical hand calculations and Finite Element Models (FEMs). Main aim of post-tensioning a glass beam is to increase its initial fracture capacity and obtain ductile post-fracture performance, which would avoid sudden collapse and provide a more desirable post-fracture performance. Galvanized steel wire rope was selected as post-tensioning member for the glass beams. Aluminum "L" shaped angles were used to connect the web and flange of the T-beams. The results of the tests were obtained, hand calculations were made, and FEM of the same types of glass beams were modeled in SAP2000. All results were compared with each other and practical design charts were obtained.

The objectives and scope of this thesis can be summarized as follows:

Objectives

1) Analytically and experimentally investigate the behavior and possible usage of glass material for structural beams.
2) Investigate and quantify use of post-tensioning for ductility of glass T-beams by conducting tests with and without post-tensioning. (Usage of reinforcement in glass beams is not an objective since initial cracking of beams is tried to be delayed using post-tensioning).
3) Investigate usage of aluminum connectors for composite action between flange and web of glass T-beams.
4) Explore and improve FE modeling capabilities to model post-tensioned composite glass beams.

5) Generate Excel based computation sheets for streamlining design process and prepare design tables for quick and simple guide to practitioner engineers.
6) Make contribution to the literature and make suggestions for future work.

Scope

1) Conduct literature survey and investigate structural use of glass in construction for beams.
2) Carry out hand calculations and design process for manageable sized T-shaped glass beams.
3) Construct FE models of each type of glass beam and obtain analysis results.
4) Planning for material and laboratory beam tests, prepare experiment setup, conduct material tests, and carry out the beam loading–capacity experiments for the following tests:
   -60mmx60mmx60mm (10-layer 6mm glass) compression tests.
   -200mmx1000mmx6mm bending tests in weak direction (float and tempered).
   -200mmx1000mmx6mm bending tests in strong direction (float).
   -100mmx1000mmx6mm bending tests in strong direction (tempered).
   -T-shaped float glass bending tests with and without post tensioning.
   -T-shaped tempered glass bending tests with and without post tensioning.
5) Post process conducted test data as Force vs Vertical Displacement Diagrams and compare with FEM and hand calculations.
6) Evaluate structural performance and make comparisons between different glass types and post-tensioning application.
7) Complete thesis writing that gathers all work conducted and underlining important outcomes for the use of glass as a structural load carrying material with post-tensioning.
8) Generate excel based computation sheets for streamlining design process and prepare tables for quick design

CHAPTER 2

MATERIAL TESTS

Although material characteristics of float and tempered glass are well documented in the literature, numerous material tests have been conducted as a part of this thesis since the design procedure highly depends on material properties and it was important to verify material properties whether they are similar to the ones listed in the literature. Major test types are listed below under each heading and primarily include compression and bending tests.

2.1. Compression Tests of Float Glass

In order to determine the compressive strength of glass, which were used in laboratory experiments, three cubes of float glass in 60x60x60 mm dimensions were tested. The cube was prepared using 6 mm thick glass pieces piled on top of each other. Ten layers of 60x60x6 mm sized glass pieces were placed as layers in order to obtain the 60x60x60 mm dimensioned cube of float glass. These pieces were slightly attached to each other with sticky tape in the circumferential direction to help during placement into the uniaxial compression test machine. One of the cubes formed by glass layers were loaded under compression by about 0.2 MPa/sec for 5 kN/sec and leading up to failure at about 962.4 kN at 3.2 minutes. The compressive stress at failure divided by the 60mmx60mm area yields a compressive strength of 267 MPa (Figure 12), which is much smaller than the 400 MPa. Two other tests were performed for the uniaxial compressive strength, which were prematurely failed at stresses in the order of 100 MPa and had partial collapse indicating some uneven stress distribution (Figure 13). Such low strength results obtained for glass tests were deemed unrealistic and the "multi-layer glass" testing approach was found to be the reason for low strength. Since having test sample sizes of 60mmx60mmx60mm or similar was not possible, uniaxial compression tests were left out of the scope of this thesis and 400 MPa available in the literature was accepted. Small irregularities of glass layers can generate unintended stress concentrations leading to premature compression failure. The performance of bending members mostly relies on the tension capacity of material and therefore more emphasis was given to bending tests of glass samples. Compression tests of tempered glass were not possible since 60mmx60mm tempered glass pieces were not possible to produce. Minimum size found for tempered glass was 200mm.

Figure 12: A glass cube before and after the compression test

Figure 13: A glass cube premature failure in the compression test

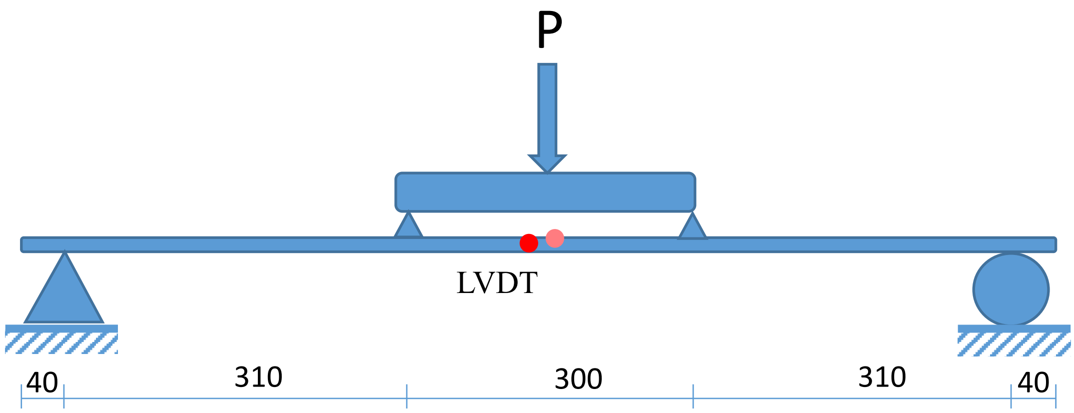
The compressive strength is calculated using Equation (1).

$$\mathit{Compressive}\ \text{Strength} = \frac{\mathit{Force}}{\text{Area}}$$

$$\sigma_{compressive} = \frac{F}{\text{A}} = \frac{962.4}{60\text{x}60}\frac{kN}{\text{mm}} = 267.33\ \text{MPa} \quad (1)$$

2.2. Bending Tests of Float and Tempered Glass

In this study, float and tempered glass samples were tested both in their weak and strong axes in order to determine the bending (indirect tension) strength of the glass used in the T-Beam tests. Specimens used for bending tests had dimensions of 1000x100x6mm and 1000x200x6 mm. Firstly, a 1000 mm long and 200 mm wide float glass sample was placed on the test set-up in its weak axis (horizontal placement) and loaded from two points until its fracture (Figure 14). The displacement transducers, Linear Variable Differential Transformer (LVDT) used for measuring the mid-span deflections of the beam were placed on either side of the beam to count for any possible torsion; average of LVDT's were used as vertical mid-span deflection of test samples. The models of these LVDT's are OPKON-LPC100, which has a stroke length of 100mm with accuracy of %0.05mm (i.e. 0.05mm). A Campbell Scientific CR1000 model data logger was used to record the applied force (F) and mid-span deflections (δ). The load cell used in this study had 3 mV/V output at full scale of 5 tons (50 kN) and could sense changes less than 5 N. The test-setup for glass samples was prepared at Strength of Materials Laboratory and loading was applied using a car-jack since the load needed to be given slowly. Mechanical arm of car-jack was a suitable choice for displacement controlled and sensitive loading of test specimens (Figure 14).



All units are in mm

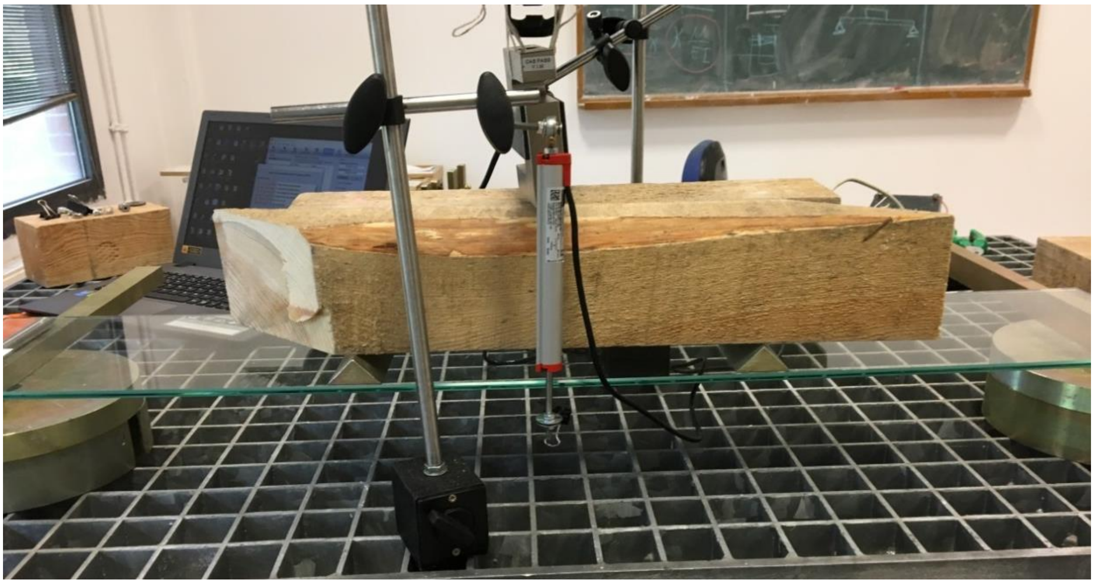


Figure 14: Loading of glass samples placed in their weak axes

The same bending test procedure was conducted on three samples of float and tempered glass. Load-displacement graphs were obtained by post-processing the data recorded from the data logger. Deflection calculations were done based on curvature diagrams as shown in Figure 15 using Moment-Area method in order to compare with the test results. Neutral axis ($\bar{y}$) of the glass sample is 3 mm from either surface. The maximum shear force and moment are calculated using Equation (2) and Equation (3), respectively. Modulus of elasticity (E) calculations are done using Equation (7) which is derived from Equation (6) by Moment-Area method. In order to calculate bending strength (σ) (indirect tension) Equation (8) is obtained by using flexure formula.

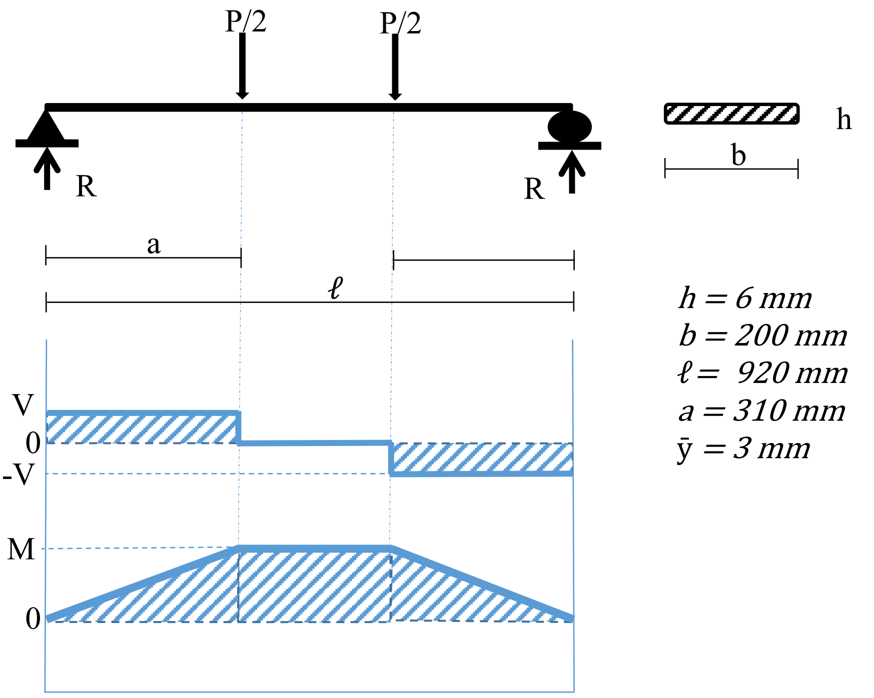


Figure 15: Shear force and moment diagrams of sample placed in its weak axis

$$R = V = \frac{P}{2} \tag{2}$$

$$M_{max} = \frac{P}{2} * a \tag{3}$$

$$\delta_{max} = \frac{\left(\frac{P}{2}\right) * a}{24 * E * I} * (3\ell^2 - 4a^2) \tag{4}$$

$$I = \frac{1}{12} * b * h^3 = \frac{1}{12} * 200 * 6^3 = 3600\ mm^4 \tag{5}$$

$$\delta_{max} = \frac{\left(\frac{P}{2}\right) * 310}{24 * E * 3600} * (3 * 920^2 - 4 * 310^2)\ \textit{(Moment Area Method)} \tag{6}$$

$$E = 3856.67 * \frac{P}{\delta_{max}}\ MPa \tag{7}$$

$$\sigma_{max} = M_{max} * \frac{\bar{y}}{I} = \frac{P}{2} * 310 * \frac{3}{3600} = 0.12917 * P\ \textit{(Flexure Formula)} \tag{8}$$

The load-displacement graphs of float glass specimen tests placed in their weak axes are given in Figure 16. Similarly, load-displacement graphs of bending tests for tempered glass samples placed in their weak axes are shown in Figure 17.

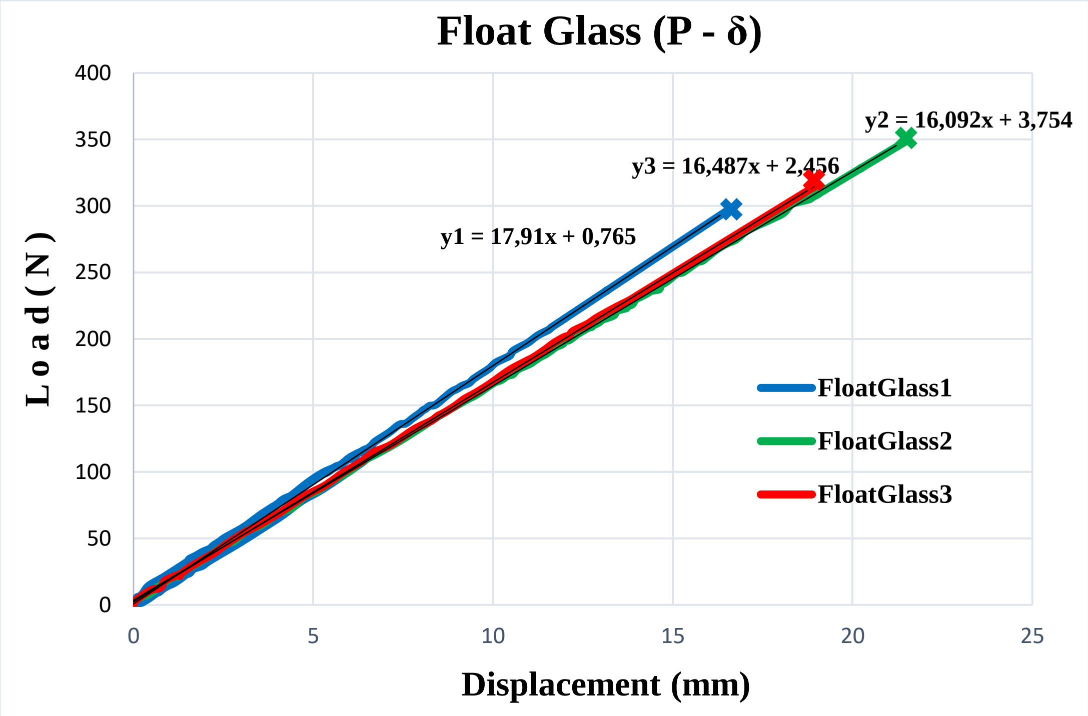


Figure 16: Load-displacement graph of float glass placed in its weak axis.

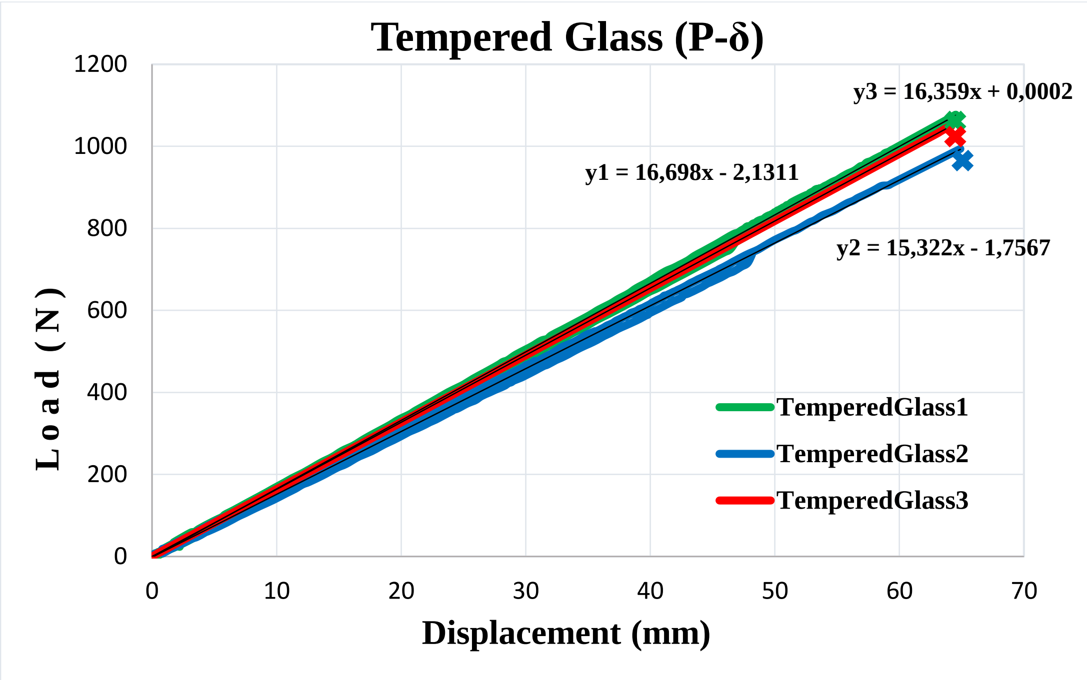


Figure 17: Load-displacement graph of tempered glass placed in its weak axis.

The maximum load (P_{max}), maximum deflection (δ_{max}), graph secant slopes and average of maximum P and δ_{max} values are presented in Table 2.

Table 2: Test results of glass samples placed in their weak axes.

Test Results					
	P_{max} (N)	δ_{max} (mm)	Secant slope of the graph	$P_{max,mean}$ (N)	$\delta_{max,mean}$ (mm)
Float Glass 1	297.4	16.57	17.90	320.1	18.99
Float Glass 2	348.3	21.46	16.11		
Float Glass 3	314.7	18.95	16.49		
Tempered Glass 1	1076.0	64.47	16.70	1039.5	64.51
Tempered Glass 2	993.9	64.89	15.32		
Tempered Glass 3	1048.5	64.16	16.36		

Resultant modulus of elasticity is calculated using Equation (7). The characteristic modulus of elasticity (with > %95 probability) obtained for float and tempered glass placed in its weak axis is 57.15 GPa and 55.74 GPa, respectively. The calculation results are tabulated in Table 3.

$$E_{characteristic} = E_{mean} - 1.645 * SD \tag{9}$$

$$E_{mean} = (E_1 + E_2 + E_3)/3 \tag{10}$$

$$SD = \sqrt{(E_{mean} - E_1)^2 + (E_{mean} - E_2)^2 + (E_{mean} - E_3)^2} \tag{11}$$

where, E_{mean}: *Mean of modulus of elasticity.*

SD: Standard deviation of modulus of elasticity.

Table 3: Modulus of elasticity calculation results of glass placed in its weak axis

Modulus of Elasticity Calculations				
	Modulus of Elasticity, E (GPa)	Modulus of Elasticity. E_{mean} (GPa)	Standart Deviation (GPa)	$E_{characteristic}$ (GPa)
Float Glass 1	69.24	65.28	4.947	57.15
Float Glass 2	62.58			
Float Glass 3	64.04			
Tempered Glass 1	64.37	62.15	3.899	55.74
Tempered Glass 2	59.07			
Tempered Glass 3	63.03			

$$\sigma_{characteristic} = \sigma_{mean} - 1.645 * SD \tag{12}$$

$$\sigma_{mean} = (\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{13}$$

$$SD = \sqrt{(\sigma_{mean-}\sigma_1)^2 + (\sigma_{mean-}\sigma_2)^2 + (\sigma_{mean-}\sigma_3)^2} \tag{14}$$

where, σ_{mean}: *Mean of max. stresses*

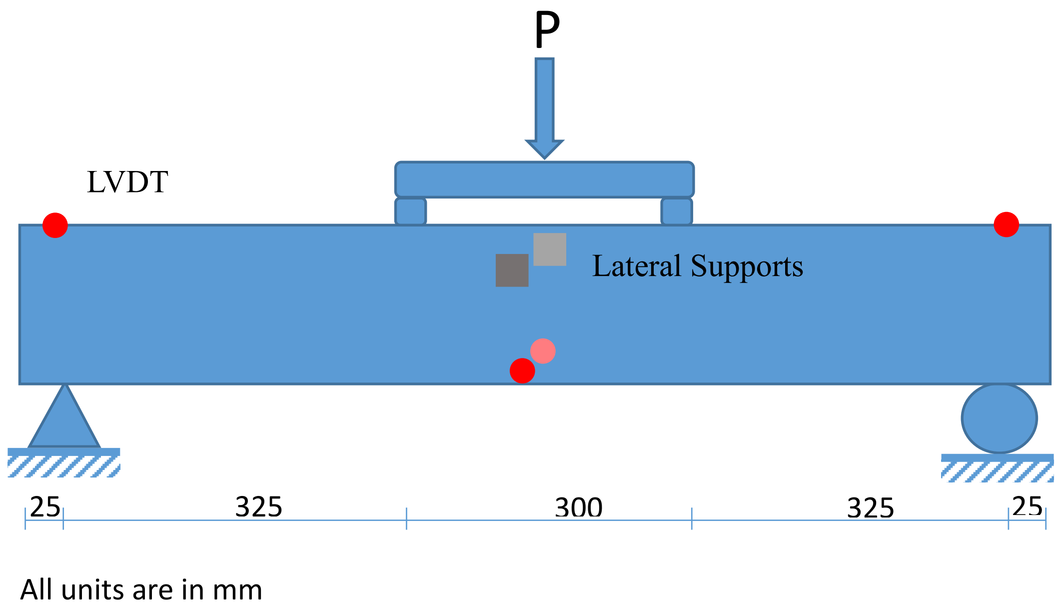
SD: Standard deviation of max. stresses

Characteristic strength is calculated according to Equation (8). It is found for float glass placed in its weak axis as 33.58 MPa, and for tempered glass placed in its weak axis as 121.70 MPa. The calculation results are listed in Table 4.

Table 4: Characteristic strength calculation results of glass placed in its weak axis

Characteristic Strength Calculations				
	σ_{max} (MPa)	$\sigma_{max.\ mean}$ (MPa)	Standart Deviation (MPa)	$\sigma_{characteristic}$ (MPa)
Float Glass 1	38.41	41.35	4.72	33.58
Float Glass 2	44.98			
Float Glass 3	40.64			
Tempered Glass 1	138.99	134.27	7.64	121.70
Tempered Glass 2	128.38			
Tempered Glass 3	135.44			

The material bending tests were also conducted in their strong axes because the aim was to see how the characteristic strength changes with respect to the glass edge placement. Glass samples with 1000x200x6 mm dimensions (float glass) and 1000x100x6 mm dimensions (tempered glass) were used in order to determine the bending (indirect tension) strength in their strong axes. Firstly, a 1000mm long and 200 mm wide float glass beam was placed on the test set-up in its strong axis and was loaded at two points with middle constant moment region until its fracture. Edge supports and loading points were cushioned using 50mmx50mmx50mm timber cubes with a 6mm wide wedge in the middle. These cubes were also secured in place by F-clamps. In order to measure the vertical mid-span deflection of the samples, two of displacement transducers were placed at the supports and two of them on either side of the beam. Moreover, the beam was restrained laterally from both sides to prevent buckling problems (Figure 18). The average value of deflection measurements for LVDT's at supports were extracted from the average value of deflection measurements for the LVDTs of the mid-span. The test-setup for glass samples was prepared at Strength of Materials Laboratory and loading was applied using a hydraulic jack.



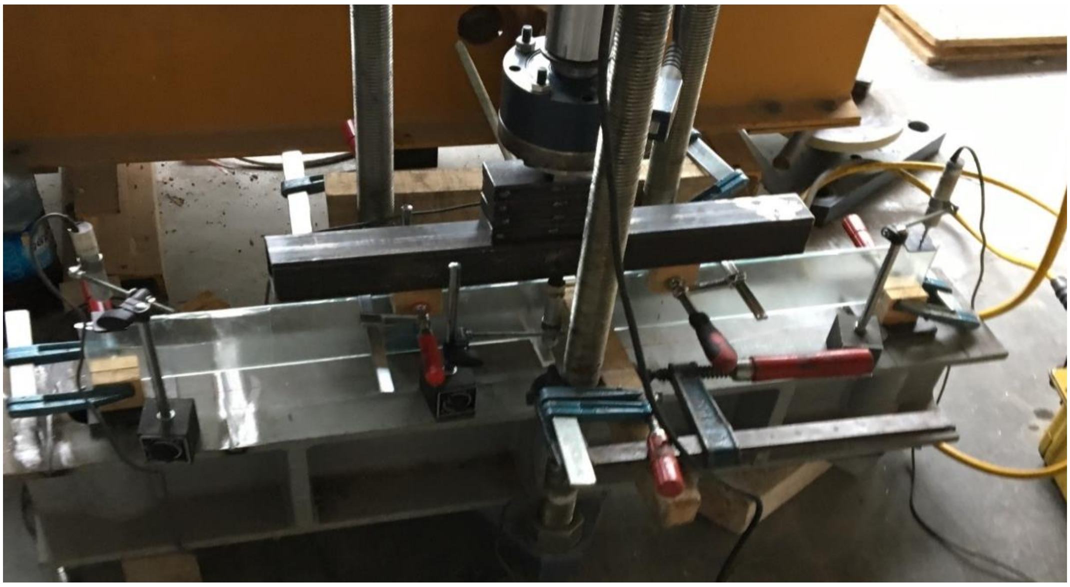
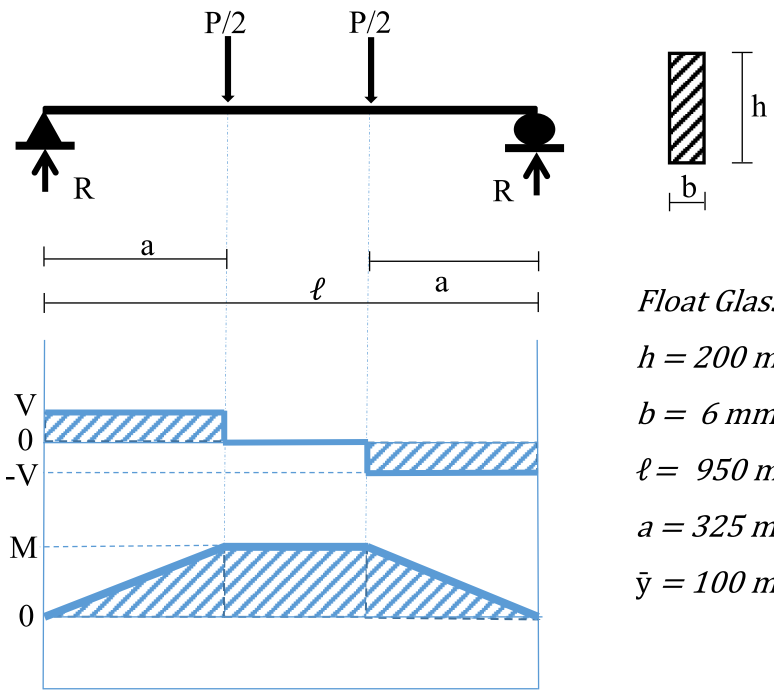


Figure 18: Loading of glass samples placed in their strong axes

The same procedure was repeated three times for samples of float and tempered glass samples. However, the dimensions for tempered glass were in 1000mmx100mmx6mm. The load-displacement graphs were obtained by post-processing the data recorded from the data logger. The calculations were done based on the shear force and moment diagrams in Figure 19 by the Moment-Area method. ȳ is calculated 100mm for float glass beam, and 50mm for tempered glass beam. The maximum shear force and maximum moment are calculated from Equation (2) and Equation (3), respectively. In order to calculate modulus of elasticity (E), Equation (17) is derived for float glass and Equation (21) is derived for tempered glass. The same way to calculate bending strength (σ) (indirect tension), Equation (18) and Equation (22) are obtained for float and tempered glass, respectively.



Float Glass	*Tempered Glass*
$h = 200\ mm$	$h = 100\ mm$
$b = 6\ mm$	$b = 6\ mm$
$\ell = 950\ mm$	$\ell = 950\ mm$
$a = 325\ mm$	$a = 325\ mm$
$\bar{y} = 100\ mm$	$\bar{y} = 50\ mm$

Figure 19: Shear force and moment diagrams of sample placed in its strong axis

Float Glass

$$I = \frac{1}{12} * b * h^3 = \frac{1}{12} * 6 * 200^3 = 4000000\ mm^4 \qquad (15)$$

$$\delta_{max} = \frac{\left(\frac{P}{2}\right) * 325}{24 * E * 4000000} * (3 * 950^2 - 4 * 325^2)\ \textit{(Moment Area Method)} \qquad (16)$$

$$E = 3.8678 \ * \frac{P}{\delta_{max}} \ MPa \tag{17}$$

$$\sigma_{max} = M_{max} \ * \frac{\bar{y}}{I} = \frac{P}{2} \ * \ 310 * \frac{3}{3600} = 0.00406 \ * P \tag{18}$$

Tempered Glass

$$I = \frac{1}{12} * b * h^3 = \frac{1}{12} * 6 * 100^3 = 500000 \ mm^4 \tag{19}$$

$$\delta_{max} = \frac{\left(\frac{P}{2}\right) * 325}{24 * E * 500000} \ * (3 * 950^2 - 4 * 325^2) \ \mathit{(Moment\ Area\ Method)} \tag{20}$$

$$E = 30.9427 \ * \frac{P}{\delta_{max}} \ MPa \tag{21}$$

$$\sigma_{max} = M_{max} \ * \frac{\bar{y}}{2} = \frac{P}{2} \ * \ 310 * \frac{3}{3600} = 0.01625 \ * P \tag{22}$$

The load-displacement graphs of float glass specimen tests placed in their weak axes are given in Figure 20. Similarly, load-displacement graphs of tempered glass samples placed in their weak axes are shown in Figure 21.

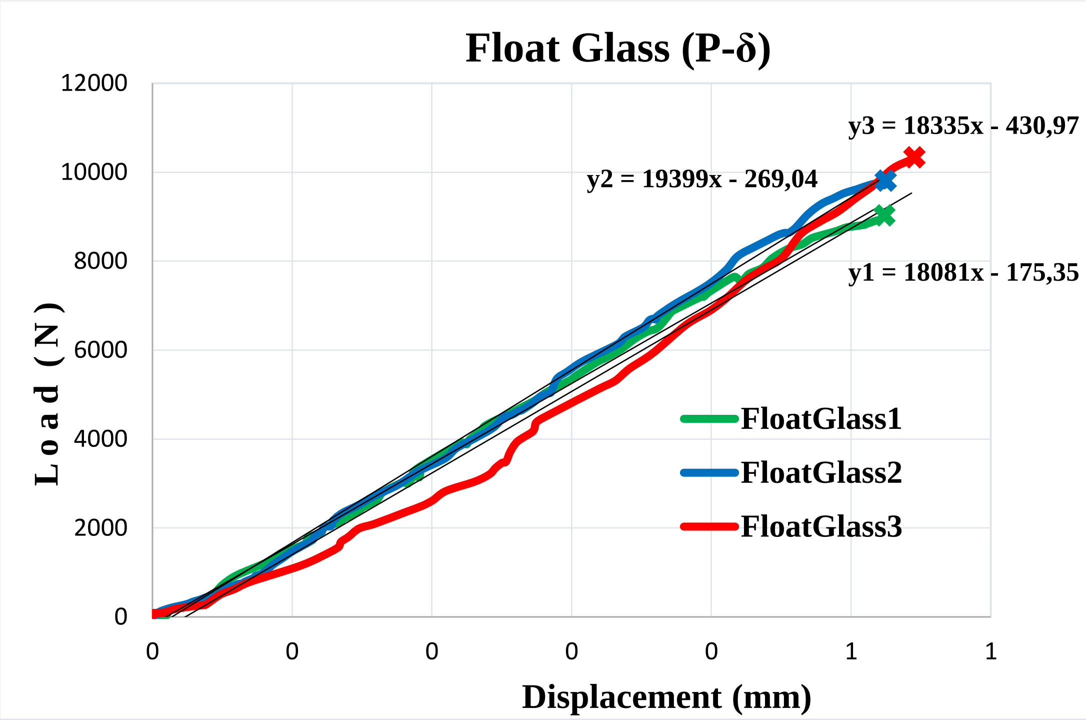


Figure 20: Load-displacement graph of float glass placed in its strong axis.

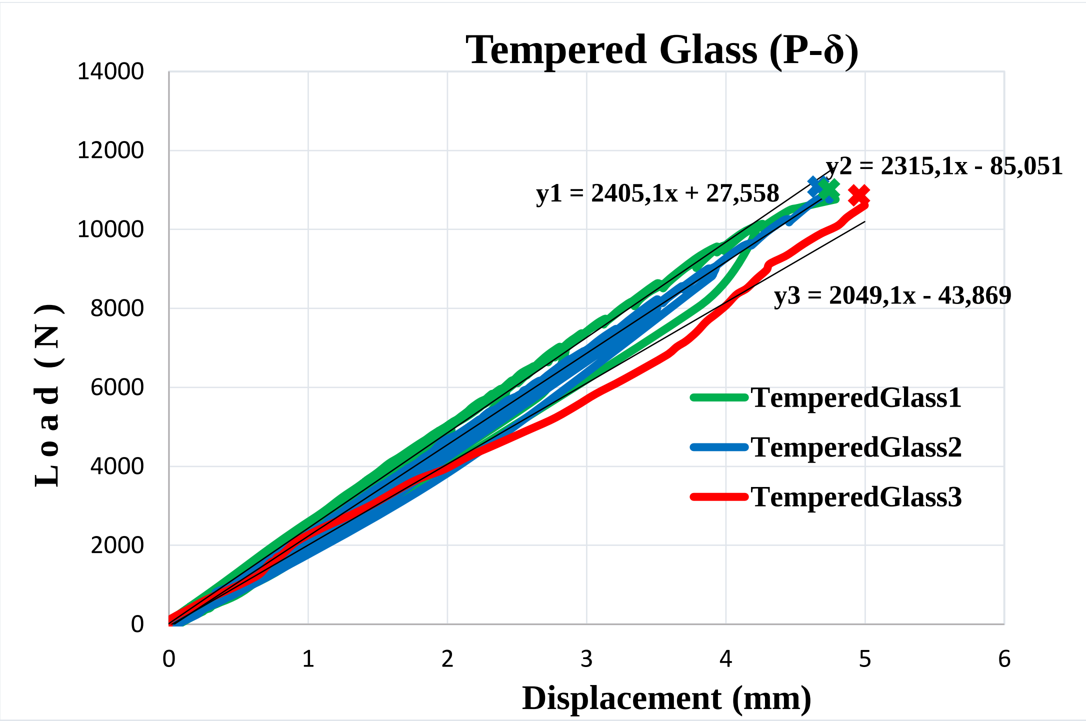


Figure 21: Load-displacement graph of tempered glass placed in its strong axis.

The maximum load (P_{max}), maximum deflection (δ_{max}), graph secant slopes and average of maximum P and δ_{max} values are presented in Table 5.

Table 5: Test results of glass samples placed in their strong axes.

Test Results					
	P_{max} (kN)	δ_{max} (mm)	Secant slope of the graph	$P_{max.mean}$ (kN)	$\delta_{max.mean}$ (mm)
Float Glass 1	8.919	0.52	18829.0	9.636	0.53
Float Glass 2	9.705	0.52	19571.0		
Float Glass 3	10.29	0.54	18335.0		
Tempered Glass 1	10.76	4.79	2405.1	10.76	4.85
Tempered Glass 2	10.90	4.78	2315.9		
Tempered Glass 3	10.61	5.00	2049.1		

Resultant modulus of elasticity is calculated by using Equation (17) for float glass and Equation (21) for tempered glass. The results of modulus of elasticity obtained for float and tempered glass placed in their strong axes are 62.10 GPa, and 62.58 GPa, respectively. The calculation results are tabulated in Table 6.

Table 6: Modulus of elasticity calculations of glass placed in its strong axis

Modulus of Elasticity Calculations				
	Modulus of Elasticity, E (GPa)	Modulus of Elasticity, E_{mean} (GPa)	Standart Deviation (GPa)	$E_{characteristic}$ (GPa)
Float Glass 1	66.39	70.44	5.071	62.10
Float Glass 2	71.70			
Float Glass 3	73.22			
Tempered Glass 1	69.52	68.62	3.673	62.58
Tempered Glass 2	70.64			
Tempered Glass 3	65.69			

Characteristic strength was calculated for samples in their strong axes according to Equation (18) for float glass and Equation (22) for tempered glass. It was found as 32.64 MPa and 169.28 MPa for float and tempered glass, respectively. The calculation results are listed in Table 7.

Table 7: Characteristic strength calculations of glass placed in its strong axis

Characteristic Strength Calculations				
	σ_{max} (MPa)	$\sigma_{max.\ mean}$ (MPa)	Standart Deviation (MPa)	$\sigma_{characteristic}$ (MPa)
Float Glass 1	36.21	39.12	3.94	32.64
Float Glass 2	39.40			
Float Glass 3	41.76			
Tempered Glass 1	174.84	174.80	3.35	169.28
Tempered Glass 2	177.15			
Tempered Glass 3	172.41			

Experimental and theoretical values of characteristic strength and modulus of elasticity for glass placed in its weak and strong axis are tabulated and compared in Table 8. At this stage, considering the beams placed in their weak and strong axes, acceptable and expected values were taken from the experiments. Moreover, the design for T-beam samples would be done with respect to the results of both in weak and strong axis. After comparison of the characteristic strengths, it is seen that tempered glass has a higher characteristic tensile strength in its strong axis, than its characteristic tensile strength in its weak axis.

Table 8: Theoretical and experimental values of characteristic strength and Modulus of Elasticity

Summary of Theoretical and Experimental Values						
	Characteristic Tensile Strength			Characteristic Modulus of Elasticity		
	Experimental (MPa)		Theoretical (MPa)	Experimental (GPa)		Theoretical (GPa)
	Weak axis	Strong axis		Weak axis	Strong axis	
Float Glass	33.58	32.64	40	57.15	62.10	70
Tempered Glass	121.70	169.27	120	55.74	62.58	70

In the T-beam calculations, characteristic strength for float glass was chosen as 32.64 MPa, and for tempered glass as 169.28 MPa. Modulus of elasticity was taken as 62.10 GPa and 62.58 GPa for float and tempered glass, respectively.

2.3. Tension Tests of Galvanized Steel Wire Rope

The other material that is used in our experiments is galvanized steel wire rope. This wire rope is used for post-tensioning the beam. A galvanized steel wire rope with 5 mm diameter was tested under tension to obtain ultimate stress capacity of the wire rope, which broke at 1500 kg (15 kN). Ultimate strength of the galvanized wire rope was calculated using Equation (23).

$$\text{Ultimate strength } (f_u) = \frac{Force}{\text{Area}} = \frac{1500*9.81}{\frac{\pi*\emptyset_{wire}{}^2}{4}} = \frac{14715\ N}{\frac{\pi*5^2}{4}} = 749.43 \text{ MPa} \quad (23)$$

That is, fracture strength of galvanized wire rope used in this study is 750 MPa. Although two wires on either side of the beam should be able to carry up to 30 kN of force, loading the wire had brought many difficulties. Initially, a load cell was manufactured using a steel pipe of Ø40x4mm and loading was planned to be applied using a large bolt, where the wire is connected to the end of the bolt and turning the end would apply tension over the load cell pulling the wire outwards. However, turning the bolt's nut was too difficult at loads beyond 10 kN. One specimen was broken during post tensioning attempts. Therefore, a hydraulic jack was used to apply the post-tensioning. Usage of a large number of clamps in the order of 5 or more and even using larger size clamps didn't yield positive results. Further attempts to secure two ends of the rope by turning or twisting has become in vain since the wire broke prematurely. Change of plans using wire grip was attempted; however, the grip sizes available to us were for larger wire diameter and no other wire grips were found in Ankara. Therefore, a larger diameter sized wire of Ø8mm had to be used together with the available wire grip in the laboratory. Using a stronger wire would lead to crushing failure of the glass flange, although a yield failure of the wire is preferred in design. The advantage of using stronger than needed wire in the tests is the possibility of using the same wire repeatedly. Compression failure of the top flange and tension failure of the high strength post-tensioning wire would have similar effect from a brittle failure point of view. High strength wires usually don't have a yielding plateau and break in a brittle manner. The fracture force of an 8 mm galvanized wire rope was calculated using Equation (24) and found to resist tension forces more than required for the T-beam tests. The same wire rope was used for all float glass and tempered glass tests and wire grips were successfully utilized. The beams have shown enough ductile behavior although steel wire rope was too strong and did not yield during loading tests. The test results and relevant discussions are provided under Chapters 4 and 5.

$$\text{Fracture Force} = \text{Max stress} * \text{Area of the wire rope}$$

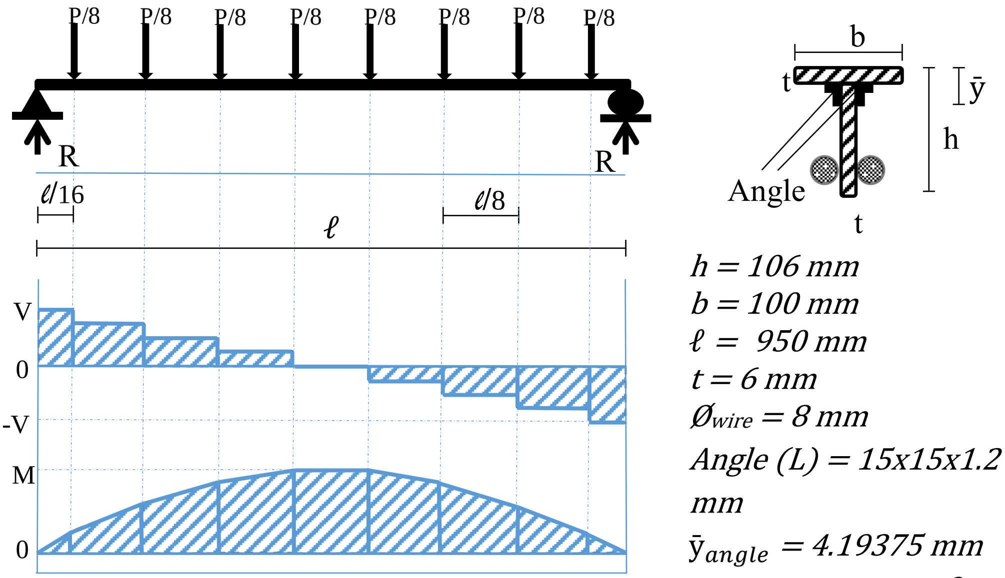
$$\mathrm{F}_{fracture} = 750 * \frac{\pi * 8^2}{4} = 37670.5 \text{ N} = 3840 \text{ kg} \tag{24}$$

CHAPTER 3

HAND CALCULATIONS AND ANALYTICAL MODELING OF T-BEAMS

3.1. Hand Calculations of T-Beam Capacity

Dimensions of the T-Beam was selected as in Figure 22 since 1000x100x6 mm dimensioned float and tempered glass sections could be obtained from the producer. Simply supported T-Beam specimens were tested under 8-point loading. There are two main reasons of loading the beam at 8 points. Firstly, there was not an 8 point loading in the literature for post tensioned glass beams which is very common to distributed load. Secondly, 8-point loading provides a typical reverse moment diagram with respect to the moment diagram due to post tensioning which is a much more feasible application for post tensioning issue. Preliminary hand calculations were done for T-Beams with and without post tensioning according to the characteristic strength and modulus of elasticity obtained from the material tests. Characteristic tensile strength for float glass was assumed as 32.64 MPa, and for tempered glass as 169.28 MPa. Modulus of elasticity was taken as 62.10 GPa and 62.58 GPa for float and tempered glass, respectively. The T-beam hand calculations and design were done with respect to the mentioned stresses. The demonstration of loading case and shear force and moment diagrams due to 8 point loading is shown in Figure 22.



$h = 106\ mm$
$b = 100\ mm$
$\ell = 950\ mm$
$t = 6\ mm$
$Ø_{wire} = 8\ mm$
$Angle\ (L) = 15x15x1.2\ mm$
$\bar{y}_{angle} = 4.19375\ mm$
$A_{angle} = 34.56\ mm^2$
$I_{angle} = 750.123\ mm^4$

Figure 22: Shear force and moment diagrams of T-Beam loaded at 8 points.

Maximum shear force, maximum moment and maximum deflection of a simply supported T-beam of 8 point loading are calculated by Equations (25), (26), and (27), respectively.

$$R = V_{max} = (8 * \frac{P}{8})/2 = \frac{P}{2} \quad \text{(Free Body Diagram)} \tag{25}$$

$$M_{max} = [\frac{P}{2} * \frac{\ell}{16}] + [(\frac{P}{2} - \frac{P}{8}) * \frac{\ell}{8}] + [(\frac{P}{2} - \frac{P}{8} - \frac{P}{8}) * \frac{\ell}{8}] + [(\frac{P}{2} - \frac{P}{8} - \frac{P}{8} - \frac{P}{8}) * \frac{\ell}{8}]$$

$$= (\frac{P\ell}{32}) + (\frac{3P\ell}{64}) + (\frac{P\ell}{32}) + (\frac{P\ell}{64}) = \frac{P * \ell}{8} \qquad \text{(Note that } dM = \int V dx\text{)} \tag{26}$$

$$\delta_{max} = [(\frac{P\ell}{32} * \frac{\ell}{16} * \frac{1}{2}) * (\frac{2\ell}{48})] + [(\frac{3P\ell}{64} * \frac{\ell}{8} * \frac{1}{2}) * (\frac{5\ell}{48})] + [(\frac{P\ell}{32} * \frac{\ell}{8}) * (\frac{8\ell}{48})] +$$
$$[\left(\frac{2P\ell}{64} * \frac{\ell}{8} * \frac{1}{2}\right) * \left(\frac{13\ell}{48}\right)] + [\left(\frac{5P\ell}{64} * \frac{\ell}{8}\right) * \left(\frac{12\ell}{48}\right)] + [\left(\frac{P\ell}{64} * \frac{\ell}{8} * \frac{1}{2}\right) * \left(\frac{19\ell}{48}\right)] +$$

$$[(\frac{7P\ell}{64} * \frac{\ell}{8}) * (\frac{18\ell}{48})] + [(\frac{8P\ell}{64} * \frac{\ell}{8} * \frac{1}{2}) * (\frac{24\ell}{48})] \tag{27}$$

$$= \frac{658}{49152} * \frac{P_{max}\ell^3}{EI_{beam}} \qquad \textit{(Moment Area Method)}$$

After getting the formulas for V_{max}, M_{max} and δ_{max} of simply supported T-beam under 8 point loading, stress checks are done in order to find the maximum load (P_{max}) that the T- beam can resist. As the failure stress is considered to be the tensile strength, maximum load carried is calculated according to tensile strength. However, the compressive strength and shear strength is also checked. This procedure was done for float and tempered glass without post tensioning according to the stress formulas given in Equations (28), (29), (30) and (31).

$$\sigma_{top} = -\frac{M_{max} * \bar{y}_{beam}}{I_{beam}} \qquad \text{(Compressive stress)} \tag{28}$$

$$\sigma_{bottom} = \frac{M_{max} * (h - \bar{y}_{beam})}{I_{beam}} \qquad \text{(Tensile stress)} \tag{29}$$

$$\tau_{neutral\ axis} = \frac{V_{max} * Q_{neutral\ axis}}{I_{beam} * t} \qquad \text{(Shear stress at neutral axis)} \tag{30}$$

$$\tau_{glue\ point} = \frac{V_{max} * Q_{glue\ point}}{I_{beam} * t} \qquad \text{(Shear stress at glue point)} \tag{31}$$

In order to find the maximum load, the tensile stress formula is used and P_{max} is calculated. The maximum deflection of the T-beam is calculated in terms of the formula found by Moment Area Method (Equation (27)).

where,

$$A_{beam} = (A_{flange}) + (A_{web}) + (2 * A_{angle})$$

$$A_{beam} = (100*6) + (100*6) + 2*34.56 = 1269.12\ mm^2 \tag{32}$$

$\bar{y}_{beam}$ = *Neutral axis is equal to the first moment divided by the total area.*

$$\bar{y}_{beam} = 106 - [(100*6*(106-3)) + (100*6*50) + (2*34.56*(100-4.19375)]/1269.12 = 28.45 \text{ mm} \tag{33}$$

$$I_{beam} = I_{flange} + A_{flange} * (y_1)^2 + I_{web} + A_{web} * (y_2)^2 + 2 * (I_{angle} + A_{angle} * (y_3)^2) \textit{ (Parallel Axis Theorem)} \quad (34)$$

where y_1, y_2, y_3 are distances from the centroids of flange, web and angle to the centroid of the beam respectively.

$$I_{beam} = \frac{1}{12} * 100 * 6^3 + 600 * (28.45 - 3)^2 + \frac{1}{12} * 6 * 100^3 + 600 * (106 - 50 - 28.45)^2 + 2 * (750.123 + 34.56 * (28.45 - 6 - 4.19375)^2 = 1370360.3\ mm^4 \quad (35)$$

$$Q_{neutral\ \mathrm{axis}} = \sum A_i * y_i = 100*6*(28.45-3)+(28.45-6)*6*(28.45-6)/2+2*34.56*(22.45-4.19375) = 18043.88\ \mathrm{mm}^3 \quad (36)$$

$$Q_{glue\ point} = 100*6*(28.45-3) = 15270\ \mathrm{mm}^3 \quad (37)$$

$$\sigma_{bottom} = \frac{M_{max} * (h - \bar{y}_{beam})}{I_{beam}} \text{ (Tensile stress)} \quad (38)$$

$$M_{max} = \frac{\sigma_{bottom} * I_{beam}}{(h - \bar{y}_{beam})} = \frac{P_{max} * \ell}{8} \quad (39)$$

$$\text{Then, } P_{max} = \frac{8 * \sigma_{bottom} * I_{beam}}{(h - \acute{y}_{beam}) * \mathrm{l}} \quad (40)$$

$$\delta_{max} = \frac{658}{49152} \frac{P_{max} \mathrm{l}^3}{E I_{beam}} \quad (41)$$

To sum up, maximum load (P_{max}) that T-beam can sustain is calculated using Equation (40) and the maximum deflection (δ_{max}) that occurs at the mid-span of T-beam is calculated using Equation (41). The calculations are done in Microsoft Excel sheets and results are tabulated in Table 9.

Table 9: Calculation results of T-beam without post tensioning

Calculation results of T-beam without post tensioning		
	Float Glass	Tempered Glass
P_{max} (kN)	4.858	25.19
δ_{max} (mm)	0.659	3.373
σ_{top} (MPa)	-11.94	-61.94
σ_{bottom} (MPa)	32.64	169.27
$\tau_{neutral\ axis}$ (MPa)	5.34	25.83
$\tau_{glue\ point}$ (MPa)	4.50	21.79

The post-tensioned glass T-beam shall be analyzed for transfer (short term) and final (long term) cases. Transfer case is the case where the beam is under its self-weight and post tensioned load, final case is the case where the beam is subjected to all loads such as post-tensioning load, live load, self-weight etc. In this study, post-tensioned float and tempered glass T-beams were tested, so the calculations were done both for design stresses and ultimate strengths. Design stresses for T-Beam with post tensioning were calculated according to Turkish Building Code Requirements for Pre-stressed Concrete (TS3233) (Table 10). Concrete has a curing time and glass has not such a strength gain time. That’s why, the allowable stresses of transfer cases were taken as final cases for glass. The ultimate strengths were taken as 32.64 MPa and 169.27 MPa for float and tempered glass, respectively.

Table 10: Allowable design stresses taken for glass in the design calculations

TS3233 Allowable Design Stresses				
Transfer Case		Float Glass	Tempered Glass	
Compression	$0.60*f_{cjk}$	240	240	MPa
Tension	$0.25*\sqrt{fcjk}$	5	15	MPa
Final Case				
Compression	0.45* fck	180	180	MPa
Tension	$0.5*\sqrt{fck}$	10	30	MPa
fcjk: Characteristic compressive strength during transfer				
fck: Characteristic compressive strength				

T-Beams with post tensioning should be analyzed under ΔM and ΔV for transfer and final cases where,

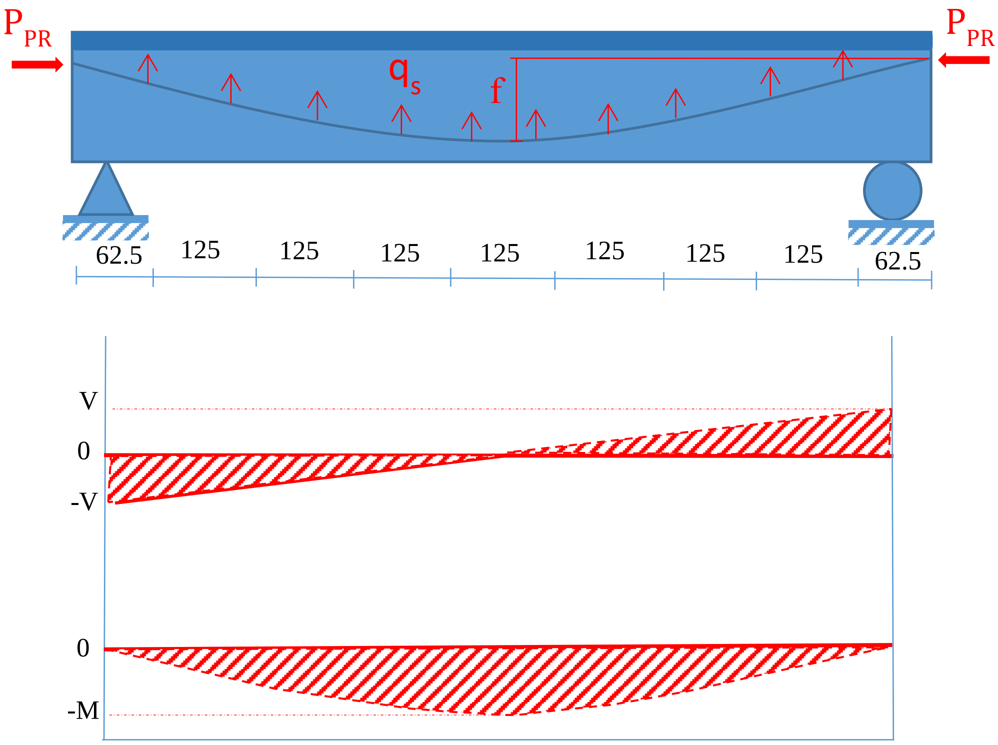
$$\Delta V_{transfer} = V_{DL}-V_{PR} \tag{42}$$

$$\Delta M_{transfer} = M_{DL}-M_{PR} \tag{43}$$

$$\Delta V_{final} = V_{FL}-V_{PR} \tag{44}$$

$$\Delta M_{final} = M_{FL}-M_{PR} \tag{45}$$

Shear force and moment diagram due to 8-point loading is shown in Figure 22 and for post-tensioning it is demonstrated in Figure 23. Both of these shear force and moment diagrams should be taken into consideration while analyzing the T-Beams with post-tensioning.



All units are in mm

Figure 23: Shear force and moment diagram due to post tensioning

The quantity of post-tensioning is calculated using Equation (48). The losses for post-tensioning were considered to be between 15%-25%. The wire rope was taken out at the neutral axis from both sides while the cover was chosen as 10 mm at the mid-span of the beam. Tensioning ratio depends on the design part but should not exceed 75% according to TS3233. Moment due to post tensioning is calculated by Equation (49) and shear force by Equation (50).

$$f = 106 - 28.45 - 10 = 67.55\ mm \tag{46}$$

$$A_{tendon} = 2 * \pi * (\varnothing_{wire})^2/4 = 2 * \pi * (8)^2/4 = 100.53\,\mathrm{mm}^2 \tag{47}$$

$$P_{PR} = (Percentage\ of\ loss) * (Tensioning\ ratio) * (f_u) * (A_{tendon}) \tag{48}$$

$$M_{PR} = P_{PR} * f = q_s * \frac{(\ell)^2}{8} => q_s = \frac{8 * P_{PR} * f}{(\ell)^2} \tag{49}$$

$$V_{PR} = q_s * \frac{\ell}{2} \tag{50}$$

Stress checks are done according to the equations for transfer and final cases (Equations 51-58). Allowable stresses for both cases were given in Table 10.

Transfer (Short term) Case

$$\sigma_{top} = \frac{-P_{PR}}{A_{beam}} - \frac{\Delta M_{transfer} * \bar{y}_{\mathrm{beam}}}{\mathrm{I}_{\mathrm{beam}}} \tag{51}$$

$$\sigma_{bottom} = \frac{-P_{PR}}{A_{beam}} + \frac{\Delta M_{transfer} * (h-\bar{y}_{beam})}{I_{beam}} \tag{52}$$

$$\tau_{neutral\ axis} = \frac{\Delta V_{transfer} * Q_{neutral}}{\mathrm{I}_{\mathrm{beam}} * t} \tag{53}$$

$$\tau_{glue\ point} = \frac{\Delta V_{transfer} * Q_{glue\ point}}{\mathrm{I}_{\mathrm{beam}} * t} \tag{54}$$

Final (Long term) Case

$$\sigma_{top} = \frac{-P_{PR}}{A_{beam}} - \frac{\Delta M_{final} * \bar{y}_{\mathrm{beam}}}{\mathrm{I}_{\mathrm{beam}}} \tag{55}$$

$$\sigma_{bottom} = \frac{-P_{PR}}{A_{beam}} + \frac{\Delta M_{final} * (h-\bar{y}_{beam})}{I_{beam}} \tag{56}$$

$$\tau_{neutral\ axis} = \frac{\Delta V_{final} * Q_{neutral}}{\mathrm{I}_{\mathrm{beam}} * t} \tag{57}$$

$$\tau_{glue\ point} = \frac{\Delta V_{final} * Q_{glue\ point}}{\mathrm{I}_{\mathrm{beam}} * t} \tag{58}$$

Maximum load ($P_{\text{design, crack or ultimate}}$) that the T-beam can sustain is calculated by Equation (62) which was derived from Equations 59, 60, and 61. This is the critical point of the T-beam's mid-span at tension zone.

$$\sigma_{bottom} = \frac{-P_{PR}}{A_{beam}} + \frac{\Delta M_{final} * (h-\bar{y}_{beam})}{I_{beam}} \tag{59}$$

$$\Delta M_{\mathrm{final}} = M_{\mathrm{final\ load}} - M_{\mathrm{PR}} \tag{60}$$

$$M_{\text{final load}} = \frac{P\text{design, crack or ultimate} * \ell}{8} = \Delta M_{\text{final}} + M_{PR} \tag{61}$$

Considering the equations above together,

$$P_{design,crack\ or\ ultimate} = \left(\frac{(\sigma_{bottom} + \frac{P_{PR}}{A_{beam}}) * I_{beam}}{(h - \bar{y}_{beam})} + M_{PR} \right) * \frac{8}{\ell} \tag{62}$$

where,

P_{design} : Design load

P_{crack} : Crack load of float glass

$P_{crack/ultimate}$: Crack and ultimate load of tempered glass

P_{design} and P_{crack} is calculated for float glass but P_{design} and $P_{crack/ultimate}$ is calculated for tempered glass only. All the calculations done in Microsoft Excel sheets are tabulated in Table 11.

Table 11: Calculation results of T-beam with post tensioning

	Calculation Results of Post tensioned T-beam				
	Design Results			**Ultimate Results**	
	Property	Float Glass	Tempered Glass	Float Glass	Tempered Glass
	P_{PR} (kN)	8.26	21.54	8.261	21.54
Transfer case	$\delta_{transfer}$ (mm)	0.62	1.60	0.62	1.60
	σ_{top} (MPa)	5.00	13.20	5.00	13.20
	σ_{bottom} (MPa)	-37.89	-99.38	-37.89	-99.38
Final case	$P_{des./crack/ult.}$ (kN)	7.157	19.28	10.53	39.97
	δ_{final} (mm)	0.35	0.98	0.81	3.754
	σ_{top} (MPa)	-12.59	-34.22	-20.68	-85.12
	σ_{bottom} (MPa)	10.20	30.20	32.30	169.47
	$\tau_{neutral\ axis}$ (MPa)	5.13	9.04	6.34	32.39
	$\tau_{glue\ point}$ (MPa)	4.33	7.63	5.34	27.32

Compared with T-beams without post-tensioning, the maximum load that the same dimensioned T-beams can resist increased from 4.86 kN to 10.53 kN for float glass and from 25.19 kN to 39.97 kN for tempered glass. Theoretically, the tensile strength capacity increased substantially after the post tensioning application.

3.2. Analytical Modeling of T-Beams

The finite element models (FEMs) of T-beams were modeled in structural software for analysis and design (SAP2000 v.20). Post tensioned float and tempered glass T-beam were modeled as well as the models without post-tensioning. Post-tensioning was applied with an 8 mm diameter wire rope from both sides of the beam. Materials and sections were defined in SAP2000; glass as thin shell with 12.5x12.5 mm mesh size, aluminum L shaped angles as frame sections, post-tensioned wire rope as tendon. Load combinations defined are as follows.

1. Dead load + Live load
2. Dead Load + Transfer case post tensioning load
3. Dead load + Live load + Final case post tensioning load

After defining the materials and sections, the T-beam was modeled as shown in Figure 24 and the maximum loads that was found for the capacity of the beams with and without post-tensioning was applied at 8 points. The material definitions, load assignments, and results were displayed for post-tensioned float glass T-beam and for the other models the results were tabulated in Table 12.

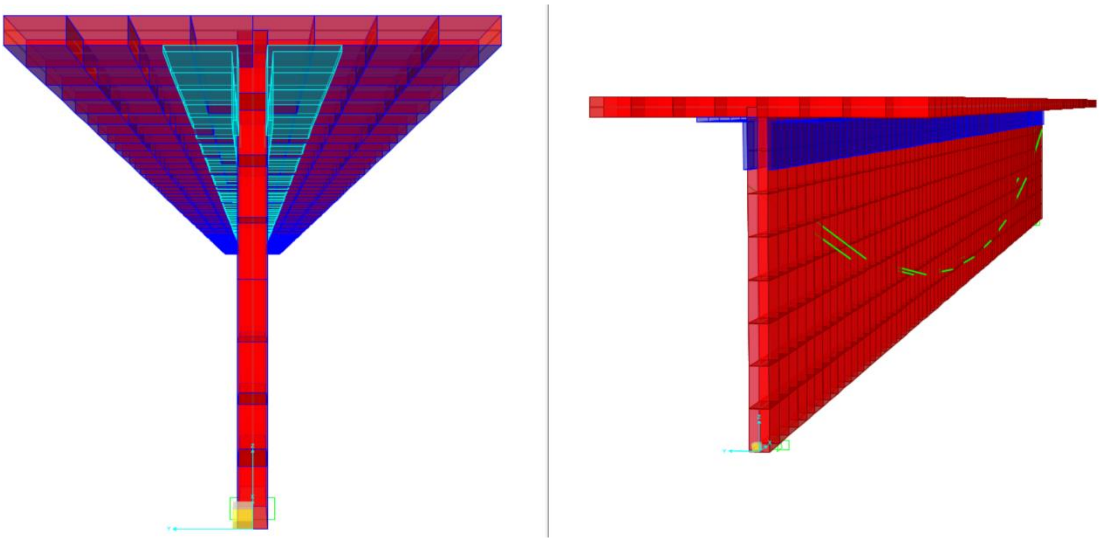


Figure 24: View of post-tensioned float glass T-beam FEM

In the T-beam FEM, firstly, glass, aluminum, and wire rope was defined. The aluminum was defined as AA6063-T6 from SAP2000 materials manual, while glass is defined as in Figure 25. Modulus of elasticity is defined as 62.10 GPa which was found from the material tests.

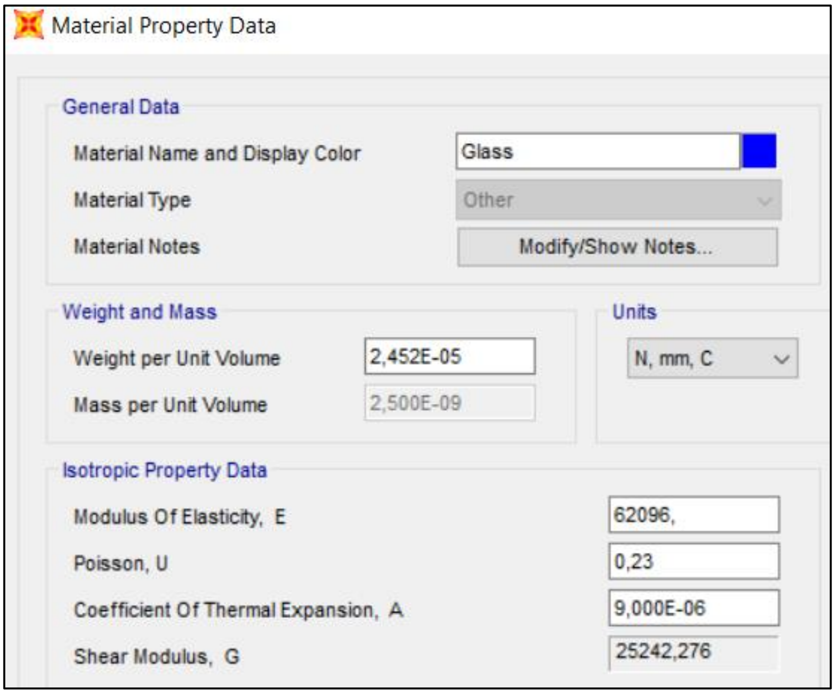


Figure 25: Material definition of float glass

The L-shaped aluminum angles were defined as 2x15x15x1.2 mm dimensioned double angle section with a back to back spacing of 6 mm (Figure 26).

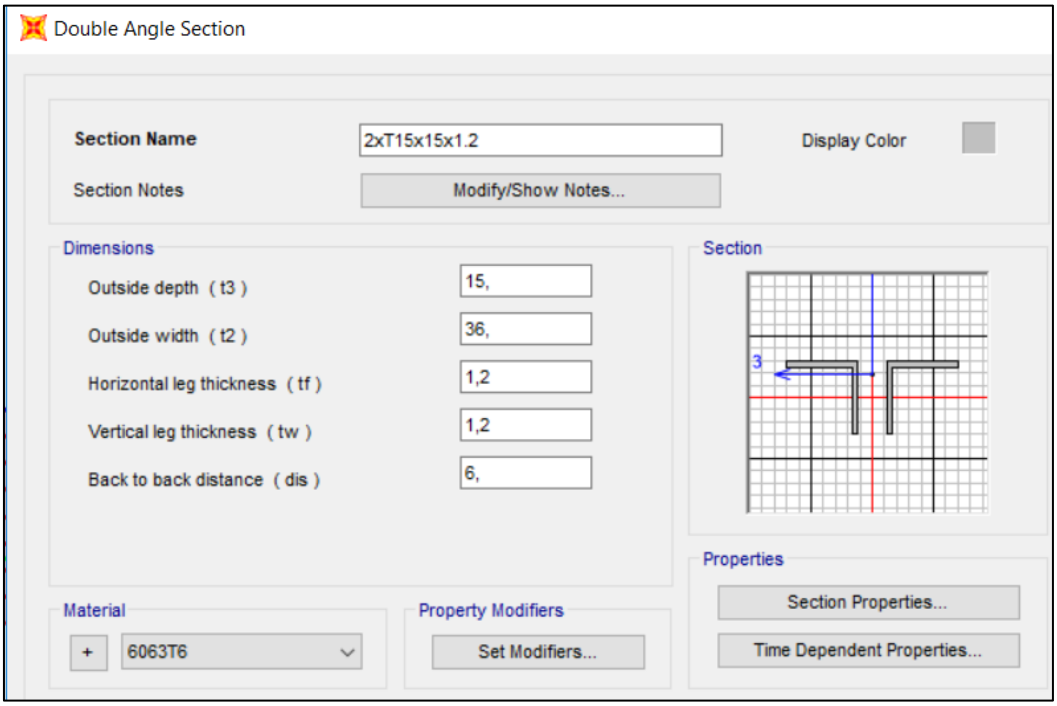


Figure 26: Double angle section definition

The maximum load at which post tensioned float glass T-beam cracks was found as 10.53 kN and the corresponding maximum tensile stress was calculated as 32.30 MPa and tabulated in Table 11. This calculated value was assigned to the finite element model as displayed in Figure 27.

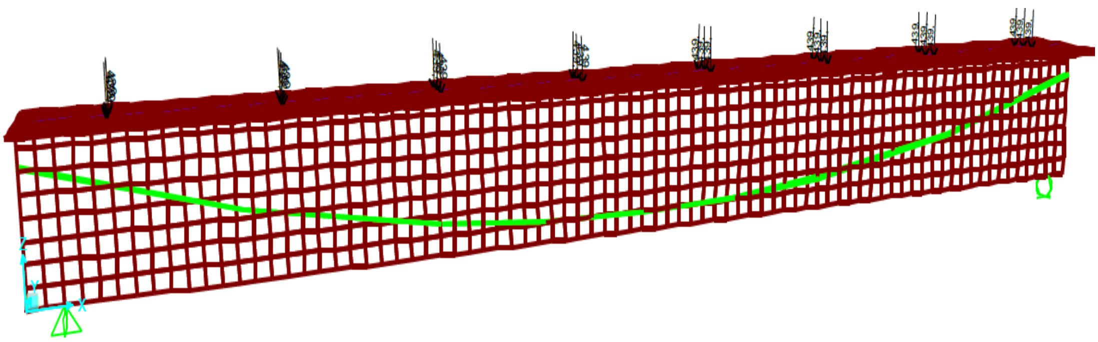


Figure 27: Load assignment of post tensioned float glass T-beam

Post-tensioning load after losses was calculated as 8.261 kN for float glass and it was assigned as load member. Loaded to the maximum load found from calculations, the stress at top and bottom of the mid-span of beam was read both at transfer and final cases. The stress distribution at transfer case of post tensioned float glass T-beam is displayed in Figure 28.

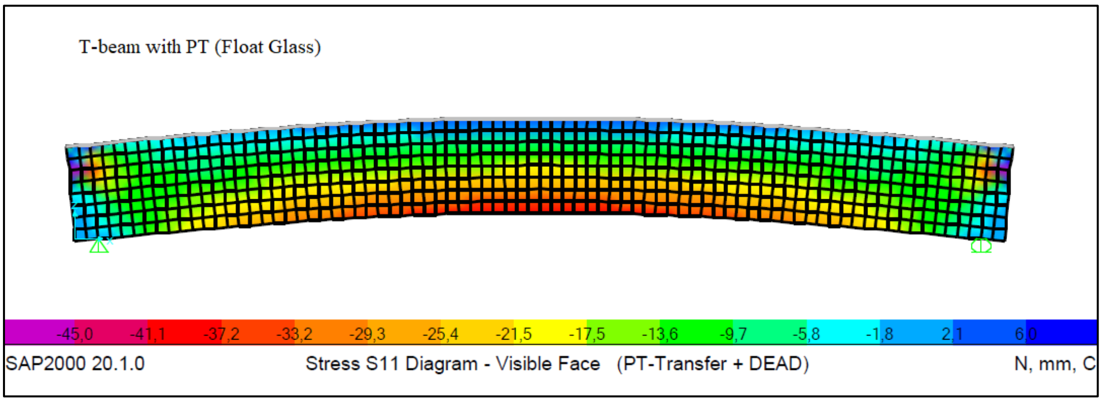


Figure 28: Stresses at transfer case of post-tensioned float glass T-beam

The stress distribution at final case of post tensioned float glass T-beam is displayed in Figure 29.

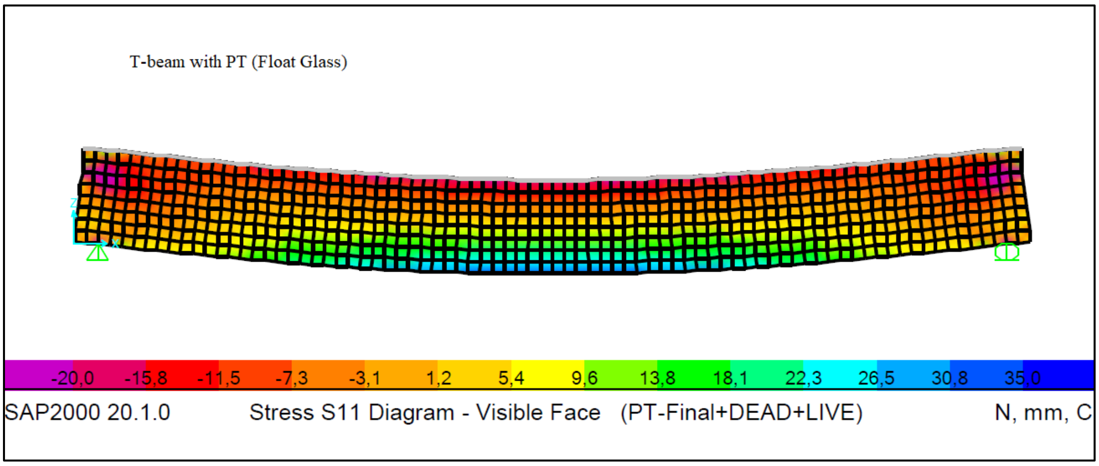


Figure 29: Stresses at final case of post-tensioned float glass T-beam

Maximum mid-span deflection of post-tensioned T-beam of float glass at final case was read from FEM analysis as 0.817 mm and the deflection distribution is shown in Figure 30.

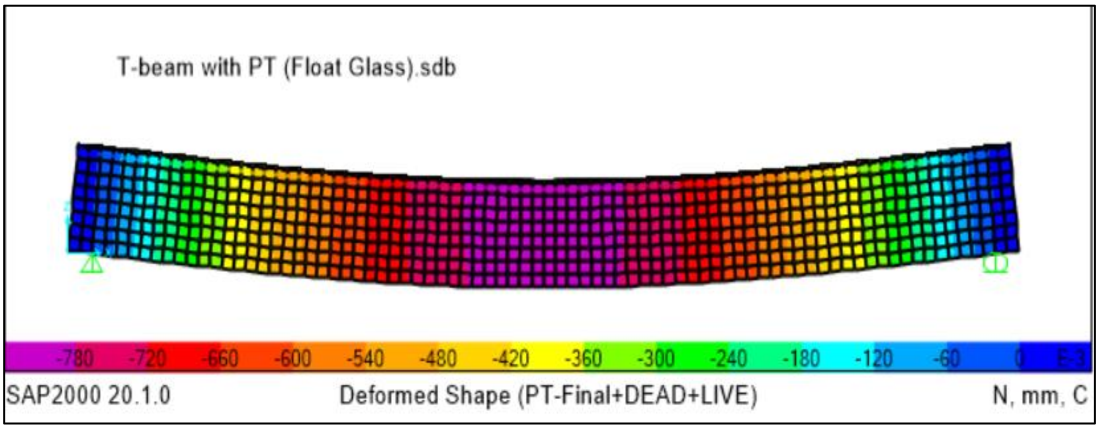


Figure 30: Deflection of post-tensioned float glass T-beam at final case

FEM results of T-beams without post-tensioning at their mid-spans are tabulated in Table 12.

Table 12: FEM results of T-beam without post tensioning

FEM Results of T-beams without Post-Tensioning		
	Float Glass	Tempered Glass
δ_{max} (mm)	0.70	3.64
$\sigma_{max,tensile}$ (MPa)	33.12	171.3
$\sigma_{max,compressive}$ (MPa)	-13.23	-68.51

FEM results of post–tensioned T-beams at their mid-spans are tabulated in Table 13.

Table 13: FEM results of T-beam with post-tensioning

FEM Results of Post-tensioned T-beams				
	Float Glass		Tempered Glass	
	Transfer Case	Final Case	Transfer Case	Final Case
δ_{max} (mm)	0.704	0.82	1.842	3.92
$\sigma_{max,tensile}$ (MPa)	4.88	32.73	12.86	169.3
$\sigma_{max,compressive}$ (MPa)	-39.22	-23.82	-103.3	-95.89

The FEM results are close to hand calculations both for float and tempered glass with and without post-tensioning. The results are compared with hand calculations and experiment outputs in section 4.3.

CHAPTER 4

TESTS OF T-BEAMS

4.1. Test Setup Design and Components

T-Beam specimens were prepared for the tests with and without post-tensioning. The web and flange of the T-Beam were 1000 mm in length, 100 mm in height, and 6 mm in thickness. The flange and web parts of the glass beam are bonded with two of aluminum L profiles in 15x15x1.2 mm dimensions by the help of polyurethane based adhesive (Akfix 610) as bonding material. The aluminum type used is aluminum alloy AA6063-T6 which has about 152 MPa shear strength. Akfix 610 is chosen as a bonding material because it is transparent, fast curing, economical, and has high bond strength. Akfix 610 conforms to D4 according to DIN EN 204. The most important point of bonding the flange and web was to fit the flange and web exactly in the same position. The T-beam was covered with transparent self-adhesive film in order to prevent its spreading away. Edge supports were cushioned using 50mmx50mmx50mm timber cubes with a 6mm wide wedge in the middle and these cubes were also secured in place by F-clamps. The beams were restrained from either side in order to prevent buckling cases. However, after the test results, it was seen that this was unnecessary for T-beam cases and it was not restrained for the rest of tests. For post tensioning 8 mm diameter galvanized steel wire rope was used in T-Beams. The post-tensioning wire rope was fed under a 30 mm diameter circular metal piece made by bronze at 8 points of both sides of the beam. These circular bronze pieces were bonded to the web of the beam with epoxy based adhesive in double syringe (Pattex Power Epoxy). It has an extremely high adhesion strength, fast curing and gap filling property, that’s why Pattex Power Epoxy is selected as bonding material. The bonding points of the metal pieces were chosen exactly under the 8 point loading locations. However, the bronze metal pieces were also secured with F-clamps from both sides. The galvanized wire ropes were anchored at the tensioning end of the beam by grips. The wire rope was continuous at the other side of the beam which was passing through an L-shaped metal piece. This metal piece was produced by two of 50x80x10 mm dimensioned metal pieces which were welded to each other at an angle of 90^0. Firstly, the anchorage detail shown in Figure 31 was applied to the beam ends. However, the couple moment shown in the free body diagram (FBD) caused the L-shaped metal piece to rotate counterclockwise as shown in Figure 31. The T-beam was moving upward from one end of it due to this rotating problem.

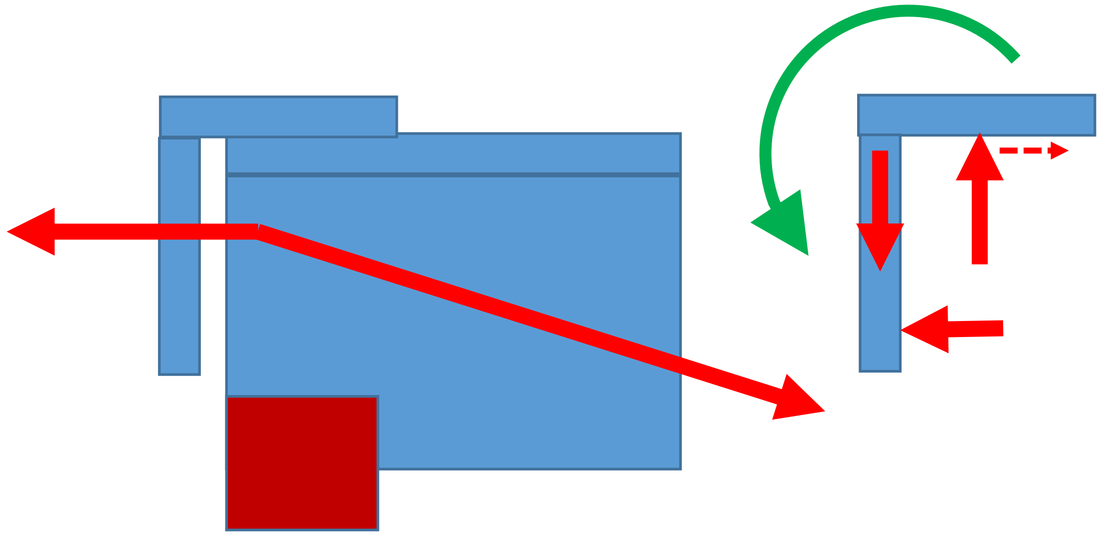


Figure 31: Anchorage detail not in equilibrium

In order to overcome this problem, L-shaped metal pieces were supported with a trapezoidal timber on the support to supply the vertical load due to post-tensioned wire rope. Moreover, a timber piece was placed between glass and the vertical metal pieces as shown in Figure 32 and this solution eliminated the rotation problem.

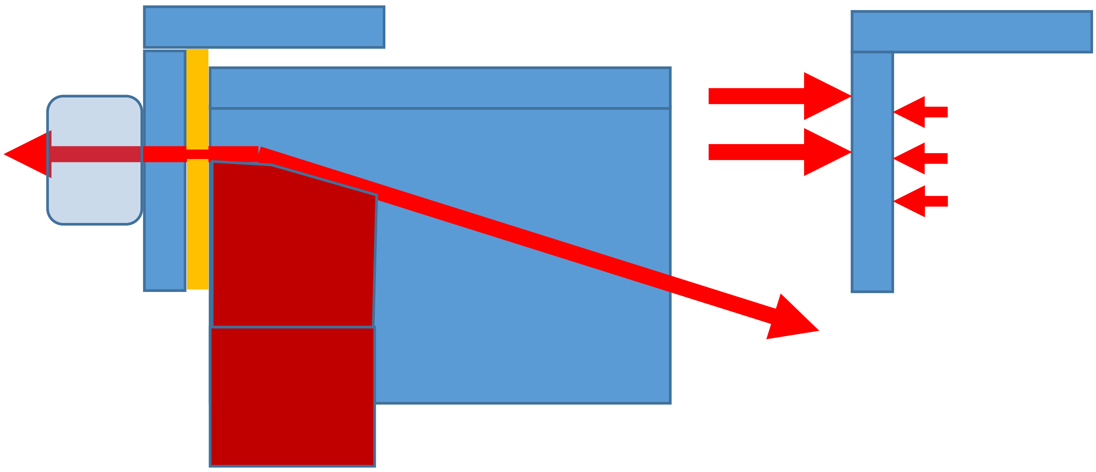


Figure 32: Anchorage detail in equilibrium

The final result of the anchorage details was compatible and acceptable. In Figure 33, at the right photo the tensioning side is given and in the middle and left side the other beam end is shown.

Figure 33: Anchorages at the ends of the beams (Tensioning at right side).

The same displacement transducers (LVDTs) were used for measuring the mid-span deflections and were placed on supports to see whether there is any crushing on the timber cubes used at beams supports. The load cell used in this study had 3 mV/V output at full scale of 5 tons (50 kN) and could sense changes less than 5 N. The geometry of the wire rope used for post tensioning was not a precisely parabolic, but it had a shape very close to parabola as shown in (Figure 34).

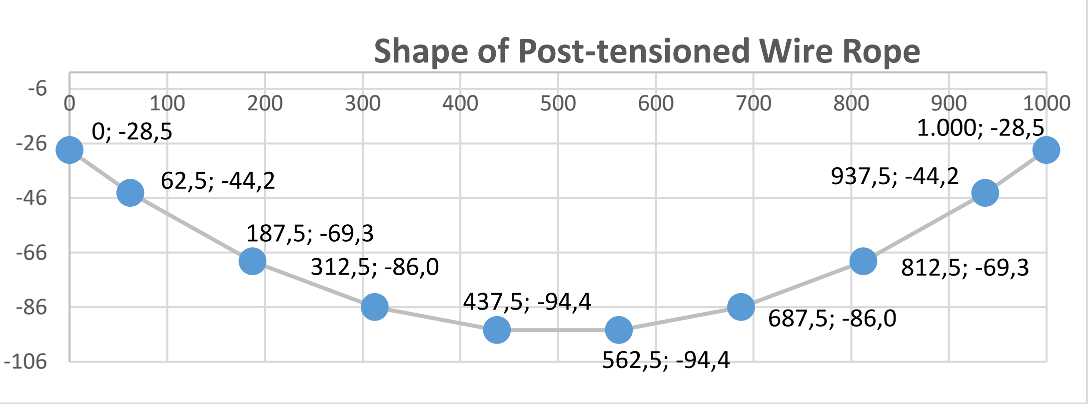


Figure 34: Geometry and coordinates of post-tensioned wire rope connectors

The set-up of T-beam without post-tensioning is displayed in Figure 35 and set-up of post-tensioned T-beam is shown in Figure 36.

Figure 35: Test set-up of T-beam without post tensioning

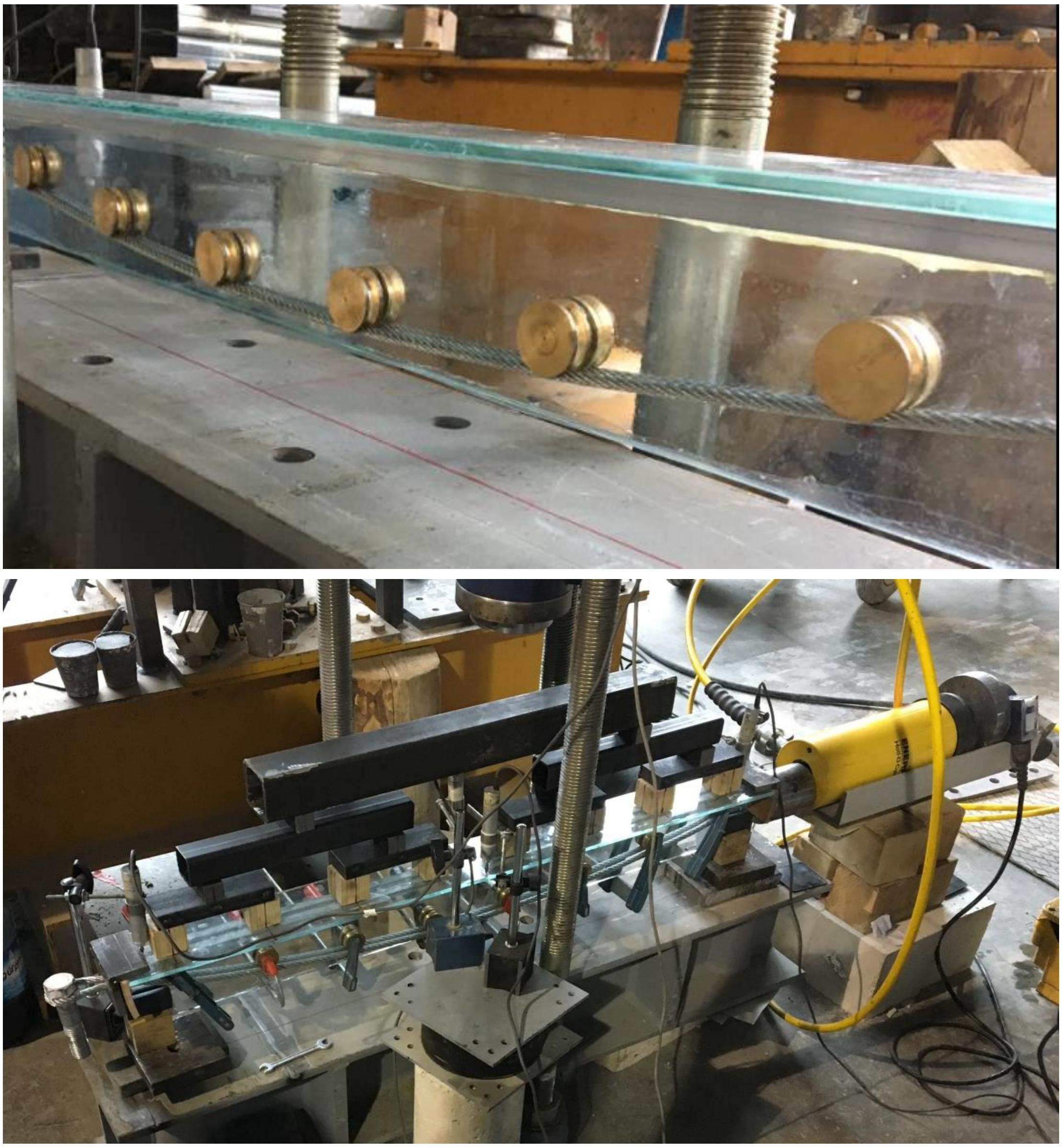


Figure 36: Test set-up of T-beam with post tensioning

4.2. Conducting the Tests and Obtaining the Results

Firstly, three specimens of each type (float and tempered) T-beams without post-tensioning tests were conducted. Some of the loading tests were conducted with several unloading cycles to see linearity and hysteresis. That's why there were some imperfections in the graphs (e.g. slight decrease in loading etc.) observed during the loading-unloading part of the tests. The float glass without post-tensioning fractured at the constant moment zone due to tensile stress after the test is conducted. The crack started at the constant moment zone of tensile area and fragmented upwards to the compression zone (Figure 37).

Figure 37: T-beam float glass exposed to its ultimate load

Tempered glass T-beam fractured into small pieces at its ultimate load without any ductility as shown in Figure 38.

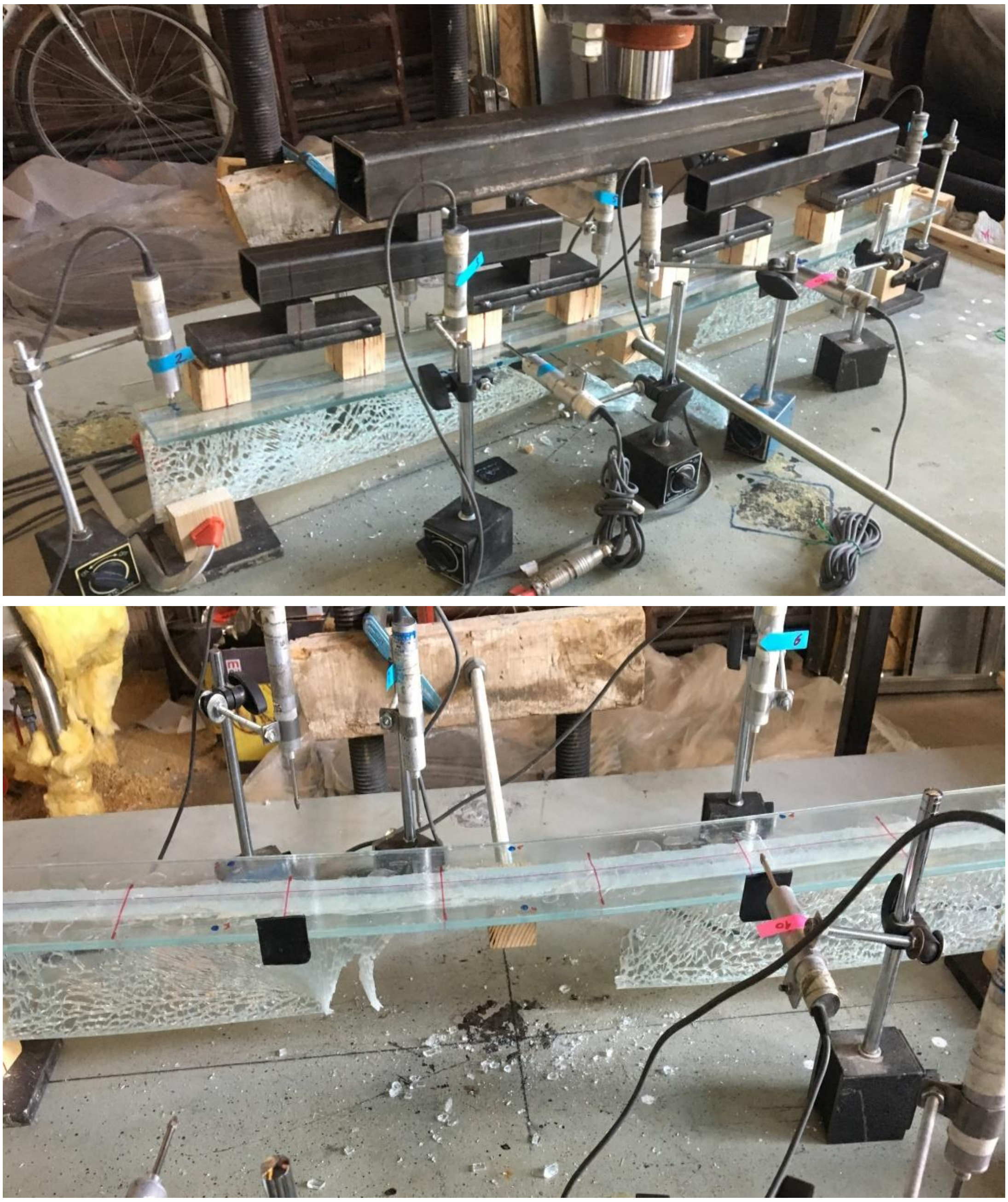


Figure 38: T-beam tempered glass exposed to its ultimate load

The load-displacement graphs of float glass T-beam specimens are given in Figure 39. Similarly, load-displacement graphs of bending tests for tempered glass T-beam are shown in Figure 40.

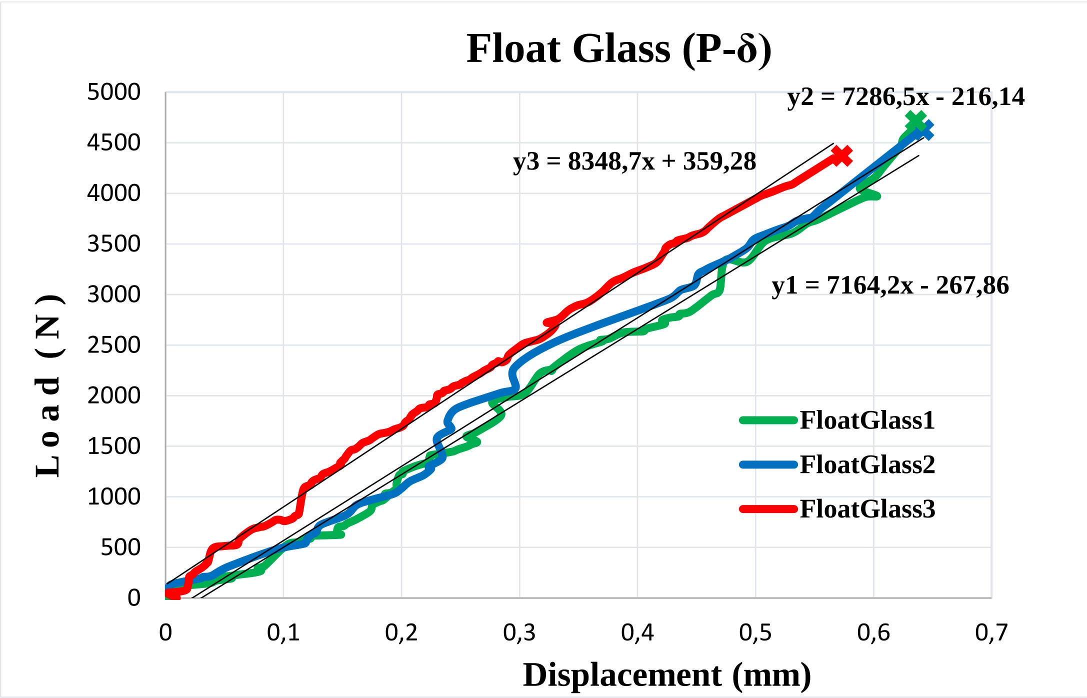


Figure 39: Load-displacement graph of float glass T-beam without post tensioning

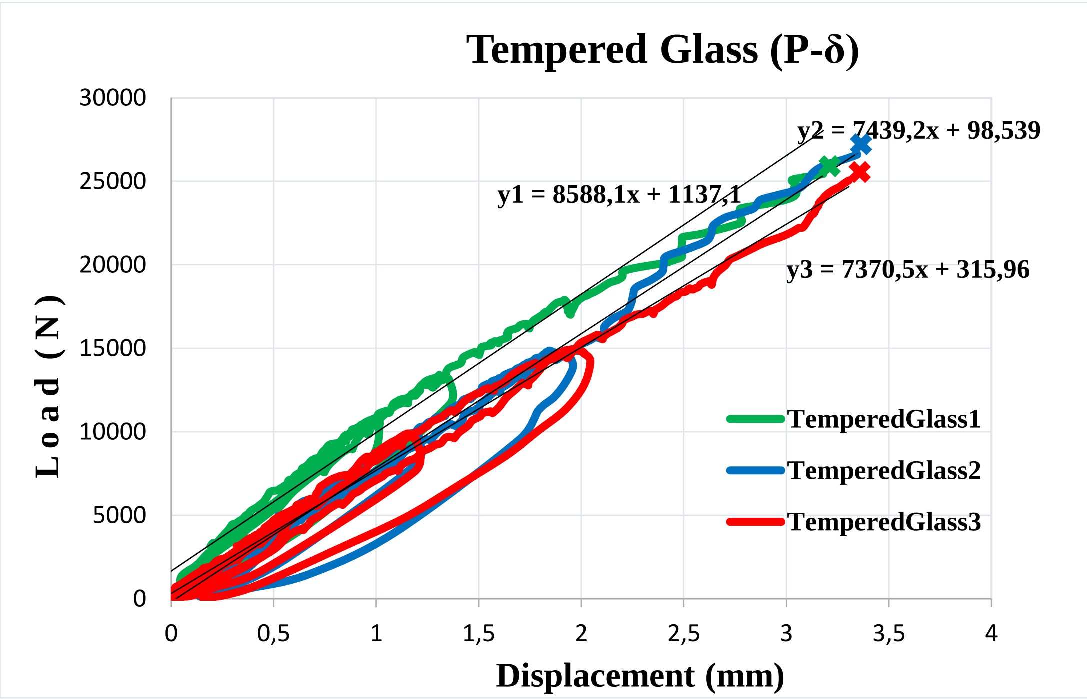


Figure 40: Load-displacement graph of tempered glass T-beam without post tensioning

The results for maximum load (P_{max}), maximum deflection (δ_{max}), graph secant slopes and average of maximum load and δ_{max} values obtained from the samples tested are tabulated in Table 14.

Table 14: Test results of T-beam without post tensioning

Test Results of T-Beams without PT					
	P_{max} (kN)	δ_{max} (mm)	Secant slope of the graph	$P_{max.mean}$ (kN)	$\delta_{max.mean}$ (mm)
Float Glass 1	4.682	0.64	7164.2	4.763	0.63
Float Glass 2	4.647	0.64	7286.5		
Float Glass 3	4.959	0.60	8348.7		
Tempered Glass 1	25.43	3.18	8588.1	25.69	3.28
Tempered Glass 2	26.60	3.35	7439.2		
Tempered Glass 3	25.05	3.30	7370.5		

Although promising results were obtained when compared with hand calculations and FEMs, modulus of elasticity and characteristic strength is calculated as it was done for samples placed in their weak and strong axes (Equation (63) and (64)). The aim was to confirm whether the T-beam concept was proper with the bonding material and aluminum L shaped angle. The results for modulus of elasticity calculations are given in Table 15 and for characteristic strength in Table 16.

$$E = 8.376 \;* \frac{P}{\delta_{max}} \;\; \text{MPa} \tag{63}$$

$$\sigma_{max} = M_{max} \;* \frac{h-\bar{y}}{I_{beam}} \;\; = 0.00672 * P \tag{64}$$

Table 15: Modulus of elasticity calculations of T-beam

Modulus of Elasticity Calculations of T-beams without PT				
	Modulus of Elasticity, E (GPa)	Modulus of Elasticity, E_{mean} (GPa)	Standart Deviation (GPa)	$E_{characteristic}$ (GPa)
Float Glass 1	61.44	63.90	7.110	52.21
Float Glass 2	60.59			
Float Glass 3	69.69			
Tempered Glass 1	66.99	65.68	2.703	61.23
Tempered Glass 2	66.57			
Tempered Glass 3	63.49			

Table 16: Characteristic strength calculations of T-beam

Characteristic Strength Calculations of T-beams without PT				
	σ_{max} (MPa)	$\sigma_{max.\ mean}$ (MPa)	Standart Deviation (MPa)	$\sigma_{characteristic}$ (MPa)
Float Glass 1	31.46	32.01	1.62	29.34
Float Glass 2	31.23			
Float Glass 3	33.33			
Tempered Glass 1	170.91	172.66	7.67	160.04
Tempered Glass 2	178.74			
Tempered Glass 3	168.32			

The results obtained were almost the same as the tests done for material tests, so the glue material used and T-beam concept was accepted. The T-beams for the post-tensioning tests were prepared in the same way as T-beam without post-tensioning. The tests conducted for T-beams with post-tensioning were the most crucial and difficult part of the study since the wire rope slipping problem had to be overcome. This problem was overcome with the grips as mentioned in Section 1.5. The T-beam was placed as shown in Figure 35 and the wire rope was tensioned to 8.25 kN for float glass and to 21.58 kN for tempered glass. Then it was loaded at 8 points until its fracture. At this point the design loads were noted as well. The tendon jack was releasing a slight part of the load and this was overcome with reloading it to the aimed post-tensioned load which was not a high proportion of the total post tensioning load. The first crack was observed at the maximum moment region in the tests of float glass with post tensioning (Figure 41) and after continuing loading more cracks were observed of the lower moment regions of the beam from bottom (tension) to top (compression) zone (Figure 42).

Figure 41: First cracks of float glass T-beam with post tensioning

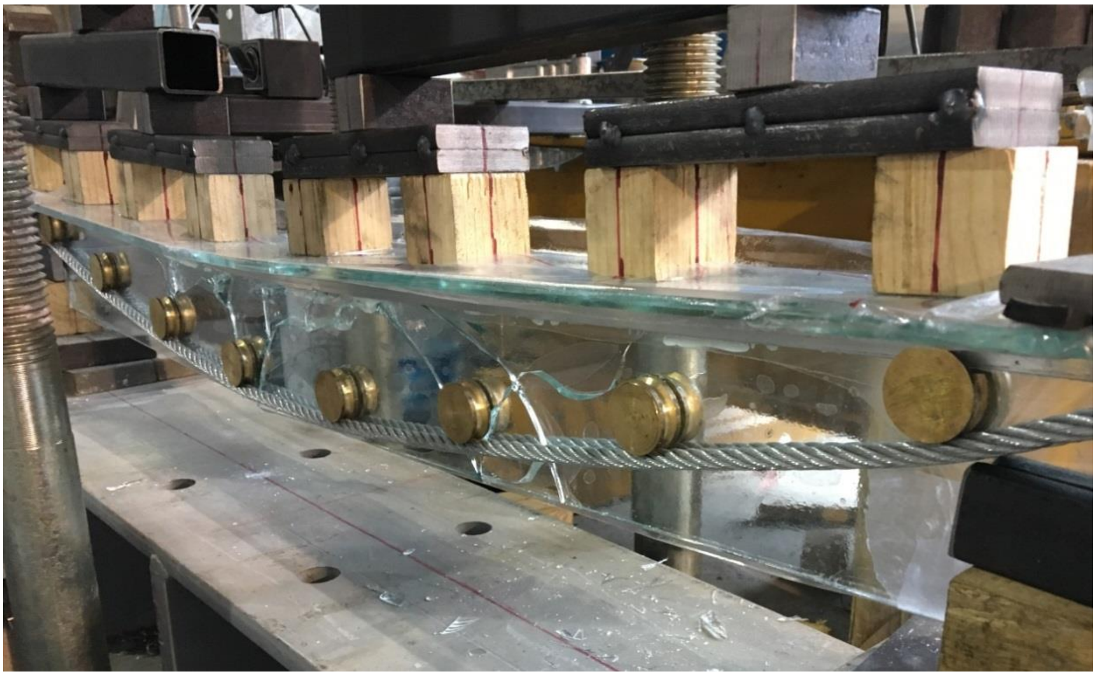


Figure 42: Float glass T-beam with post-tensioning after fracture.

The tempered glass T-beam with post-tensioning fractured in small pieces at its crack/ultimate load as shown in Figure 43.

Figure 43: Tempered glass T-beam with post tensioning after fracture.

The load-displacement graph of float glass T-beam samples with post tensioning are given in Figure 46-48. The graphs show how the mid-span of the beam deflects with post-tensioning and loading. The upward direction was assumed as positive deflection and downward as negative deflection.

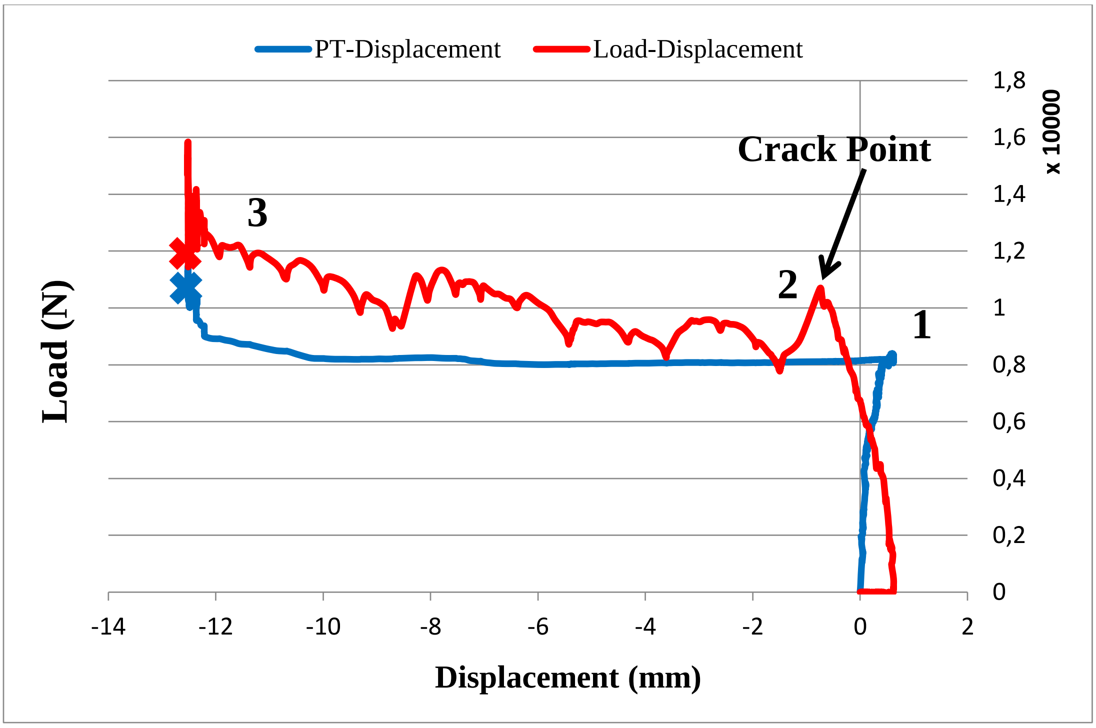


Figure 44: Load-displacement graph of float glass T-beam with PT (1)

The first sample of post-tensioned float glass T-beam was tensioned to the designed value of post-tensioning. The beam deflected upward at its mid-span to the value of 0.62 mm corresponding to 8.25 kN post-tensioning *(Point 1 in Figure 44).* Then, the beam was loaded at 8 points and it cracked at 10.86 kN corresponding to 0.749 mm downward deflection at its mid-span *(Point 2 in Figure 44).* The first cracks occurred at constant zone which includes the mid-span of the beam. While the sample was kept on loading more cracks occurred along the length of it *(Between points 2 and 3 in Figure 44.).* At 15.72 kN the beam was unloaded at 12.5 mm deflection at its mid-span.

The tests for second and third samples of post-tensioned float glass T-beams were conducted the same way as in the first sample. The results for these samples are shown in Table 17.

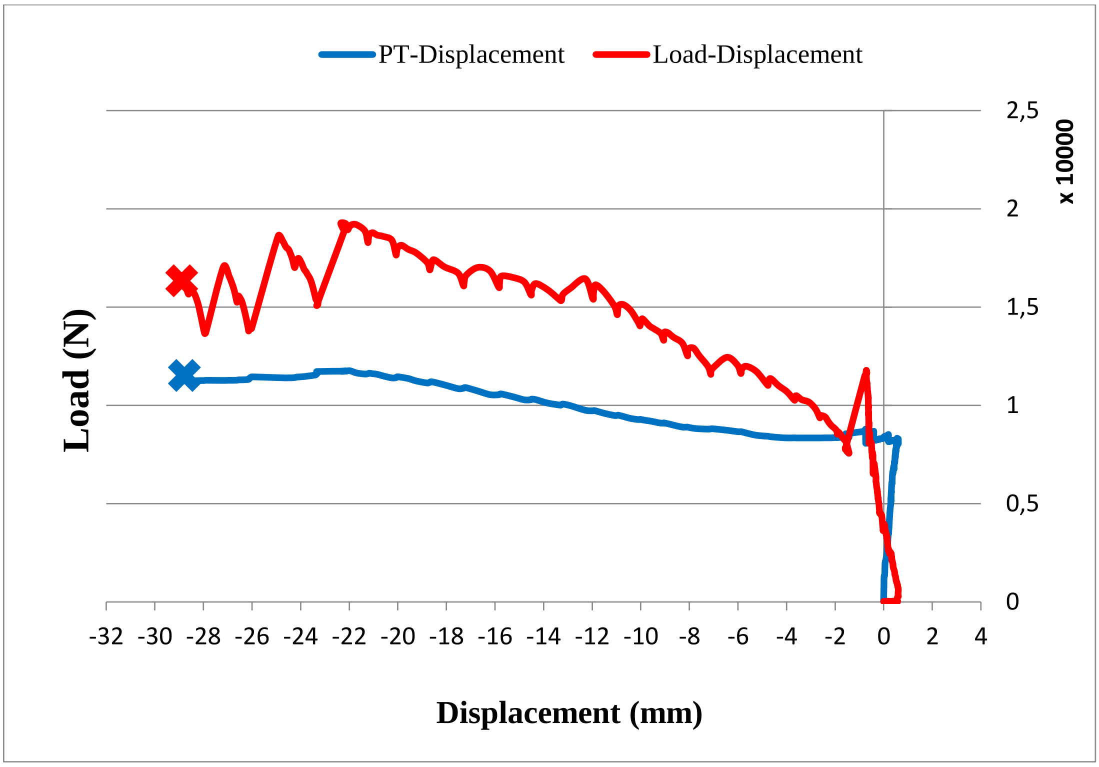


Figure 45: Load-displacement graph of float glass T-beam with PT (2)

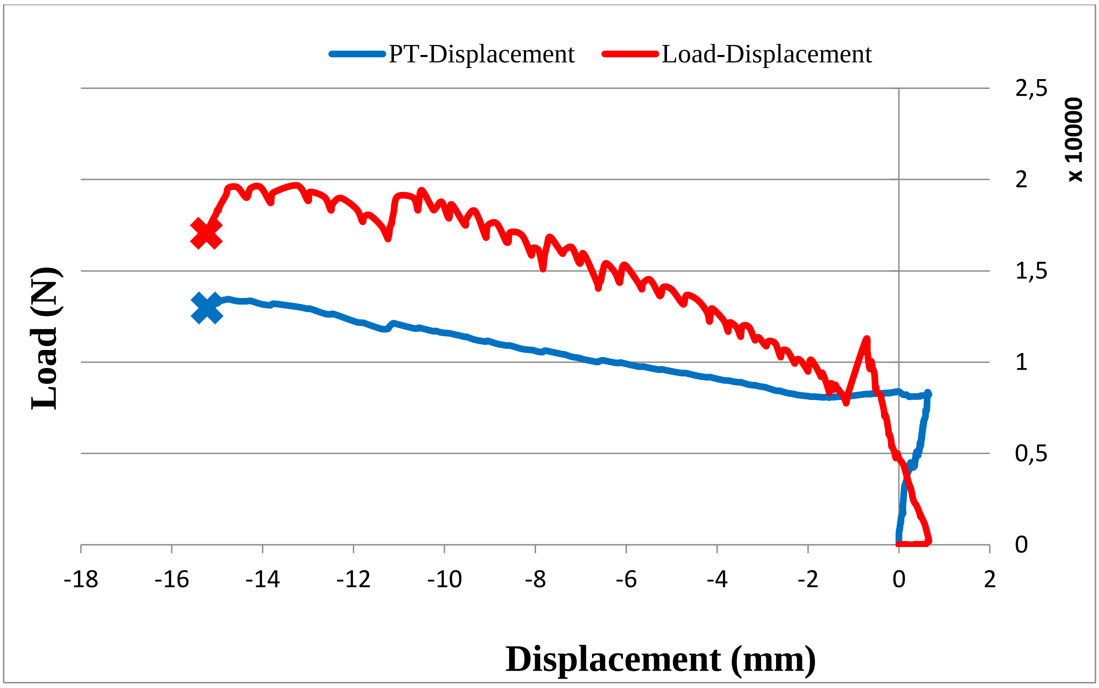


Figure 46: Load-displacement graph of float glass T-beam with PT (3)

The procedure done for post-tensioned float glass T-beam was repeated for post-tensioned tempered glass T-beam as well.

The first sample of post-tensioned tempered glass T-beam was tensioned to the design post-tensioned load 21.54 kN. The sample deflected upward with a value of 1.66 mm (*Point 1 in Figure 47).* Then, the beam was loaded at 8 points and it started to deflect downward. The first sample cracked at 37.98 kN corresponding to 4.26 mm downward deflection at its mid-span. This was also the ultimate load that the beam could sustain since tempered glass has an explosive breakage which results in very small pieces of glass *(Point 2 in Figure 47).* One specimen of tempered glass was broken during post tensioning attempts. That's why, two post-tensioned tempered glass beam samples were conducted.

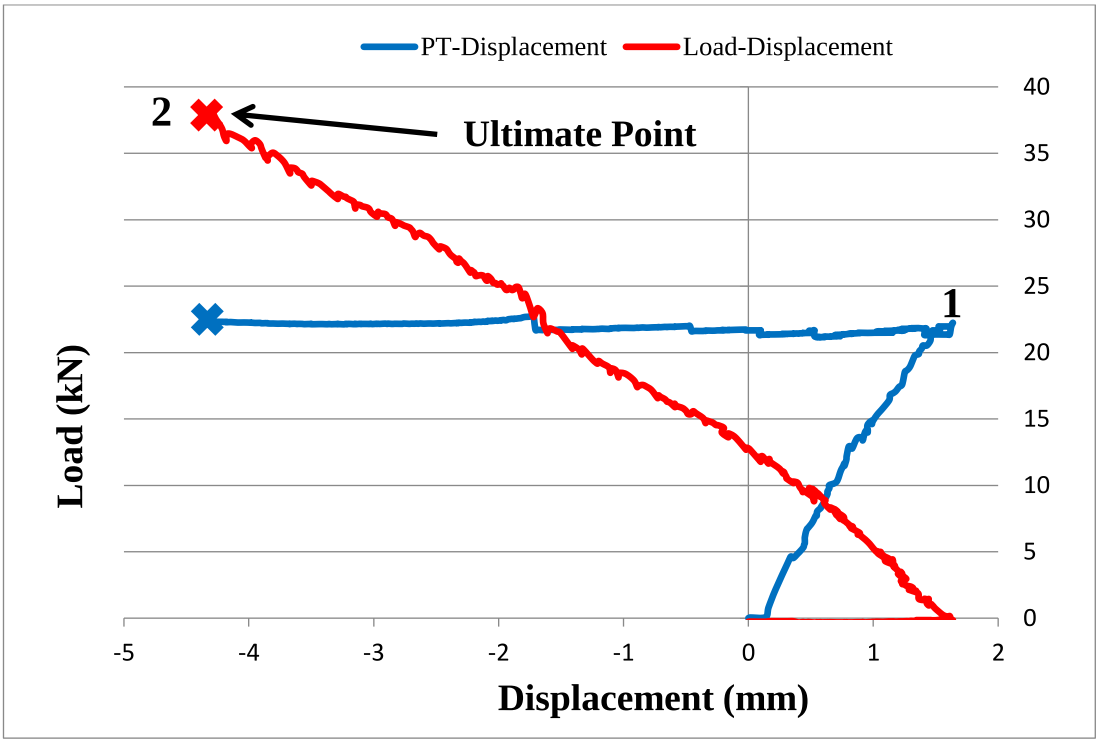


Figure 47: Load-displacement graph of tempered glass T-beam with PT (1)

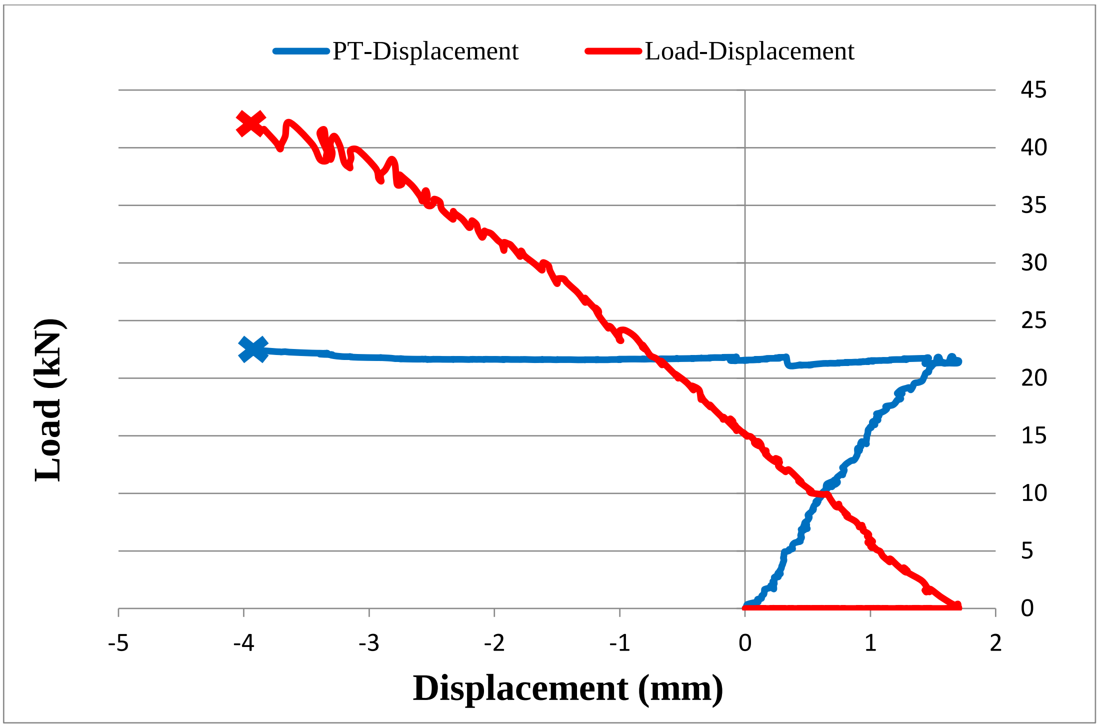


Figure 48: Load-displacement graph of tempered glass T-beam with PT (2)

The test results of post-tensioned T-beams are shown in Table 17.

Table 17: Results of post tensioned T-beam tests

Test Results of post-tensioned T-Beams					
	$P_{crack/ultimate}$ (kN)	$\delta_{max.final}$ (mm)	$\delta_{max.transfer}$ (mm)	$P_{max.mean}$ (kN)	$\delta_{max.\ final\text{-}.mean}$ (mm)
Float Glass 1	10.68	-0.749	0.619	11.14	-0.751
Float Glass 2	11.52	-0.779	0.571		
Float Glass 3	11.23	-0.724	0.628		
Tempered Glass 1	37.98	-4.260	1.663	39.79	-4.049
Tempered Glass 2	41.61	-3.839	1.706		

Float glass beam with post tensioning sample tests resulted in ductile behaviors (Figure 46). The maximum load that it could sustain was 19276.7 N which is about 1.7 times than crack load. However, tempered glass tests had brittle failure (Figure 48). The average results for T-beam tests are summarized below (Table 18).

Table 18: Summary of T-beam test results

Summary of T-beam Test Results				
	T-beam without PT		T-beam with PT	
	Float Glass	Tempered Glass	Float Glass	Tempered Glass
$P_{crack/ultimate}$ (kN)	4.763	25.69	11.143	39.79
δ_{max} (mm)	0.63	3.28	0.75	4.05

The T-beams with and without post tensioning were compared according to the glass type and post-tensioning. First of all, it should be noted that, the average loads were taken into account while comparing the test results. To begin with, float glass without post tensioning fractured at 4.763 kN with a brittle failure. Also, tempered glass without post tensioning had a brittle failure at 25.69 kN which was 5.39 times higher compared with the same dimensioned float glass T-beam. Tempered glass T-beam with post tensioning had also a brittle failure but at a 1.55 times higher load (39.79 kN) compared with the same tempered glass T-beam without post tensioning. The capacity increase of the maximum load that T-beams with post tensioning can resist depends on the post tensioning design such as the tensioning ratio, the quantity of the wire rope etc. However, a more preferable result was obtained from post tensioned float glass which had a ductile failure. The crack load was 11.15 kN which is 2.34

times higher than the same beam without post tensioning. Moreover, the ultimate load was recorded as 19.28 kN, 4 times higher than the load float glass T-beam without post tensioning can sustain. The comparisons between different types of the same dimensioned T-beams according to test results are displayed in a column chart in Figure 49.

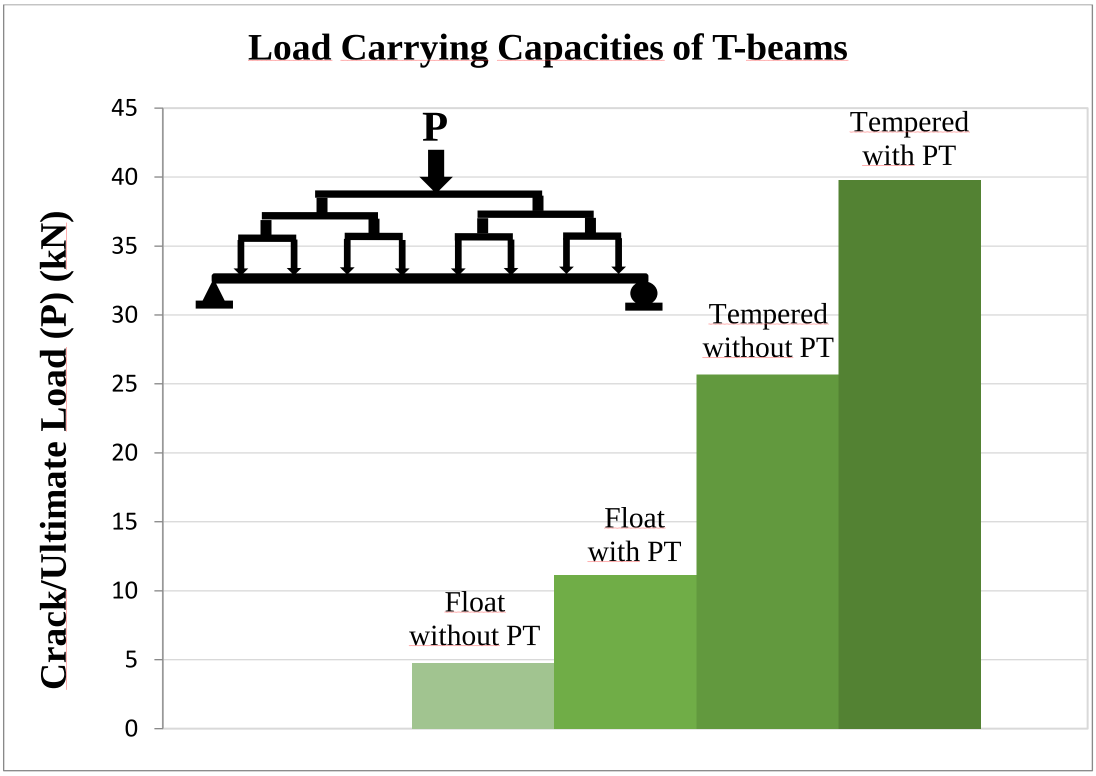


Figure 49: Load carrying capacities of the same dimensioned T-beams

4.3. Comparison of Tests, Analytical Models and Hand Calculations

In this section the results for T-beam of finite element models (FEMs), hand calculations and experiments were compared with load-deflection behavior. The results were tabulated in Table 19 for T-beam without post tensioning and in Table 20 for post tensioned T-beam. It should be noted again that the results for tests were the average results of the samples.

Table 19: Summary of the results for T-beam without post tensioning according to hand calculations, FEMs, and tests

Summary of the Results for T-beam without PT Results				
	Float Glass		Tempered Glass	
	$P_{crack/ultimate}$ (kN)	δ_{max} (mm)	$P_{crack/ultimate}$ (kN)	δ_{max} (mm)
Hand Calc.	4.858	0.66	25.19	3.37
FEM	4.858	0.704	25.19	3.64
Test	4.763	0.63	25.69	3.28

Table 20: Summary of the results for post tensioned T-beam according to hand calculations, FEMs, and tests

Summary of the Results for T-beam with PT Results				
	Float Glass		Tempered Glass	
	$P_{crack/ultimate}$ (kN)	δ_{max} (mm)	$P_{crack/ultimate}$ (kN)	δ_{max} (mm)
Hand Calc.	10.53	0.81	39.97	3.75
FEM	10.53	0.82	39.97	3.92
Test	11.14	0.75	39.79	4.05

Comparison of hand calculations and FEM analyses with the test results showed good correlation in the range of about ±3%. These results can be deemed as in well agreement, considering that the glass test results had a scatter of about ±4%. It can be concluded that both hand calculations and FEMs are valid for the design of post-tensioned glass T-beams.

CHAPTER 5

SUMMARY AND CONCLUSION

The main aim of this study is to make contribution to the literature of structural glass with and without post-tensioning. The thesis includes analytical and experimental work of a T-shaped glass beam taking post-tensioning into consideration. Purpose of post-tensioning of T-beams is to increase initial fracture capacity and obtain a more ductile post-fracture performance, which would avoid sudden collapse and provide a more desirable post-fracture performance. One of the best outcomes of this study is due to the fact that float glass post cracking strength can be drastically increased and a ductile post-cracking performance can be obtained.

In this study, firstly, several material tests were conducted in order to confirm the theoretical mechanical properties of glass for compression and bending (indirect tension) strength. The values specified from the material tests were used in the conducted experiments of the T-shaped glass beams.

Three cubes of float glass in 60x60x60 mm dimensions made by placing 10 layers of 60x60x6mm glass were tested in a uniaxial compression test machine in order to determine compressive strength of float glass. Although surface impurities of glass layers reduce the compressive strength, the compressive stress at failure divided by the 60mmx60mm area yielded a compressive strength of 267 MPa (Figure 12), which is much smaller than the 400 MPa capacity obtained from the literature. Compression tests were deemed unrealistic and the “multi-layer glass” testing approach was found to be the reason for low strength and compression tests results were rejected, while the 400 MPa compressive strength that is available in the literature was accepted.

Float and tempered glass samples were tested in bending for their both weak and strong axes in order to determine the bending (indirect tension) strength of the glass used in the T-Beam tests. The samples were loaded from two points until their fracture and the results were recorded. Characteristic tensile strength and modulus of elasticity are calculated according to moment area method and flexure formula. The results are listed in Table 8. The 5 percentile characteristic tension strength for float glass was found as 32.64 MPa and for tempered glass it was specified as 169.28 MPa. Modulus of elasticity was calculated as 62.10 GPa and 62.58 GPa for float and tempered glass, respectively. Compared with theoretical values, they are deemed realistic and were taken into account for the T-beam hand calculations and tests. At this point, it should be noted that, tensile strength of tempered glass in its strong axis was higher than in its weak axis (169 MPa vs 120 MPa, respectively). The value obtained from its strong axis was taken into account because in the T-beams tension member's orientation was in vertical orientation (strong direction).

After deciding the characteristic values from the material tests, Finite Element Models (FEM) of the T-beams are modeled and analytical hand calculations are done for the same types of glass beams. Then, T-shaped annealed (float) and tempered (toughened) glass beams with and without post-tensioning were tested under 8-point loading.

According to the flexure formula, the maximum load that the T-beams without post-tensioning can resist was found as 4857.5 N and 25190.5 N for float and tempered glass beams, respectively. These loads were assigned to the finite element models in SAP2000 and the stresses were found as 33.12 MPa and 171.25 MPa for float and tempered glass, respectively.

The experiment results for float and tempered glass without post-tensioning are found as 4762.7 N, 25692.4 N, respectively. The crack stresses are 29.34 MPa for float glass and 160.04 MPa for tempered glass. According to flexure formula the maximum load that the T-beams without post-tensioning can resist was found as 10530.1 N, 39965.8 N for float and tempered glass, respectively. These loads were assigned to the finite element models in SAP2000, and the stresses were found as 32.73 MPa and 169.65 MPa for float and tempered glass, respectively.

The maximum crack load for float and tempered glass with post-tensioning is recorded as 11.14 kN, and for tempered glass with post-tensioning is recorded 39.79 kN.

The following conclusions are obtained:

- Comparison of the hand, FEM analyses and tests results gave close values; therefore, analyses are close to the experimental results showing confidence for design.
- Although the capacity of tensile strength increased in tempered glass T-beam, at its ultimate strength it fractured and collapsed suddenly.
- Post-tensioned float glass beam can be considered to have a better post-fracture performance, which avoids sudden collapse and provides a safer failure. This application may have revealed that post-tensioned float glass shows similar behavior as reinforced concrete beams.
- The ultimate strength for post-tensioned float glass was improved by about 73 % of the cracking strength.
- The cracking strength of post-tensioned float glass was improved by about 134 % of the without post-tensioning strength.
- The ultimate strength for post-tensioned tempered glass was improved by about 55% of the without post-tensioning strength.
- The cracking and ultimate deflections as well as the linear extrapolation of cracking force and ultimate force had a ratio in the order of 15. This shows a much superior post-cracking performance compared to ordinary structures.
- Design tables formed to guide practitioners were shown to be useful for selecting reasonable beam member sizes and thicknesses (Appendix A).

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APPENDICES

A. TABLES FOR QUICK DESIGN OF POST-TENSIONED GLASS T-BEAM

Design Tables for Post-Tensioned Glass T-Beams

[Table for 2 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Distance between beams (mm)											
	500			1000			1500			2000		
	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	0.7	no need	1.3	1.7	L0.8x0.8x0.5	2.7	2.5	L2.0x2.0x1.0	4.2	----	----	----
1500	0.9	no need	1.9	2.0	L0.8x0.8x0.5	4.0	2.9	L1.8x1.8x1.0	6.1	3.6	L3.0x3.0x1.5	8.3
2000	1.0	no need	2.6	2.3	L0.8x0.8x0.5	5.3	3.3	L1.8x1.8x0.9	8.1	4.1	L2.8x2.8x1.5	11.0
2500	1.2	no need	3.2	2.5	no need	6.6	3.6	L1.6x1.6x0.9	10.1	4.4	L2.6x2.6x1.4	13.7
3000	1.3	no need	3.9	2.7	no need	8.0	3.8	L1.6x1.6x0.9	12.1	4.8	L2.6x2.6x1.3	16.4
3500	1.4	no need	4.6	2.8	no need	9.3	4.0	no need	14.2	5.0	L2.4x2.4x1.3	19.1
4000	1.5	no need	5.2	3.0	no need	10.7	4.2	no need	16.2	5.2	no need	21.8
4500	1.5	no need	5.9	3.1	no need	12.0	4.3	no need	18.2	5.4	no need	24.5
5000	1.6	no need	6.6	3.2	no need	13.4	4.5	no need	20.3	5.6	no need	27.3
5500	----	----	----	3.2	no need	14.8	4.6	no need	22.4	5.8	no need	30.0
6000	----	----	----	3.3	no need	16.2	4.7	no need	24.5	5.9	no need	32.8
6500	----	----	----	3.4	no need	17.6	4.8	no need	26.6	6.0	no need	35.6
7000	----	----	----	3.4	no need	19.0	4.9	no need	28.7	6.1	no need	38.5
7500	----	----	----	3.5	no need	20.5	4.9	no need	30.9	6.2	no need	41.3
8000	----	----	----	3.5	no need	21.9	5.0	no need	33.0	6.3	no need	44.2
8500	----	----	----	3.5	no need	23.4	5.1	no need	35.2	6.4	no need	47.1
9000	----	----	----	3.6	no need	24.8	5.1	no need	37.4	6.5	no need	50.0
9500	----	----	----	3.6	no need	26.3	5.2	no need	39.6	6.6	no need	53.0
10000	----	----	----	3.6	no need	27.8	5.2	no need	41.8	6.6	no need	55.9
10500	----	----	----	----	----	----	5.2	no need	44.1	6.7	no need	58.9
11000	----	----	----	----	----	----	5.3	no need	46.4	6.7	no need	62.0
11500	----	----	----	----	----	----	5.3	no need	48.7	6.8	no need	65.0
12000	----	----	----	----	----	----	5.3	no need	51.0	6.8	no need	68.1

* The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values. Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

** Sections are calculated by assuming 2 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).

*** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.

**** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.

***** Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.

Figure A. 1: Design table of post-tensioned glass T-beam for 2 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 2 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

	Width (mm)											
	2500			3000			3500			4000		
Length (mm) - Beam depth=Length/10	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	----	----	----	----	----	----	----	----	----	----	----	----
1500	4.3	L4.1x4.1x2.1	10.6	----	----	----	----	----	----	----	----	----
2000	4.8	L3.9x3.9x2.0	14.0	5.4	L5.0x5.0x2.6	17.0	----	----	----	----	----	----
2500	5.2	L3.7x3.7x2.0	17.3	5.9	L4.8x4.8x2.5	21.0	6.6	L5.9x5.9x3.1	24.7	----	----	----
3000	5.6	L3.5x3.5x1.9	20.7	6.3	L4.6x4.6x2.4	25.1	7.0	L5.7x5.7x3.0	29.5	7.7	L6.8x6.8x3.6	33.9
3500	5.9	L3.4x3.4x1.8	24.1	6.7	L4.4x4.4x2.3	29.1	7.5	L5.5x5.5x2.9	34.2	8.2	L6.6x6.6x3.4	39.4
4000	6.2	L3.2x3.2x1.7	27.5	7.0	L4.2x4.2x2.2	33.2	7.8	L5.3x5.3x2.8	39.0	8.6	L6.3x6.3x3.3	44.9
4500	6.4	L3.1x3.1x1.6	30.9	7.3	L4.1x4.1x2.1	37.3	8.2	L5.1x5.1x2.7	43.8	8.9	L6.1x6.1x3.2	50.3
5000	6.6	no need	34.3	7.6	L3.9x3.9x2.1	41.4	8.4	L4.9x4.9x2.6	48.6	9.3	L5.9x5.9x3.1	55.9
5500	6.8	no need	37.8	7.8	L3.8x3.8x2.0	45.6	8.7	L4.7x4.7x2.5	53.5	9.6	L5.7x5.7x3.0	61.4
6000	7.0	no need	41.3	8.0	no need	49.8	8.9	L4.6x4.6x2.4	58.3	9.8	L5.5x5.5x2.9	67.0
6500	7.2	no need	44.8	8.2	no need	54.0	9.2	L4.4x4.4x2.3	63.3	10.1	L5.4x5.4x2.8	72.6
7000	7.3	no need	48.3	8.4	no need	58.2	9.4	no need	68.2	10.3	L5.2x5.2x2.8	78.2
7500	7.4	no need	51.9	8.5	no need	62.5	9.5	no need	73.2	10.5	L5.1x5.1x2.7	83.9
8000	7.5	no need	55.5	8.7	no need	66.8	9.7	no need	78.2	10.7	no need	89.6
8500	7.7	no need	59.1	8.8	no need	71.1	9.9	no need	83.2	10.9	no need	95.4
9000	7.8	no need	62.7	8.9	no need	75.5	10.0	no need	88.3	11.0	no need	101.2
9500	7.8	no need	66.4	9.0	no need	79.9	10.1	no need	93.4	11.2	no need	107.0
10000	7.9	no need	70.1	9.1	no need	84.3	10.3	no need	98.6	11.3	no need	112.9
10500	8.0	no need	73.8	9.2	no need	88.8	10.4	no need	103.8	11.5	no need	118.8
11000	8.1	no need	77.6	9.3	no need	93.3	10.5	no need	109.0	11.6	no need	124.8
11500	8.1	no need	81.4	9.4	no need	97.8	10.6	no need	114.3	11.7	no need	130.8
12000	8.2	no need	85.2	9.5	no need	102.4	10.7	no need	119.6	11.8	no need	136.9

* The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values. Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

** Sections are calculated by assuming 2 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).

*** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.

**** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.

***** Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.

Figure A. 2: Design table of post-tensioned glass T-beam for 2 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 3.5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Distance between beams (mm)											
	500			1000			1500			2000		
	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	1.5	L0.7x0.7x0.4	2.3	2.8	L2.5x2.5x1.3	4.9	3.8	L4.7x4.7x2.5	7.6	4.5	L6.9x6.9x3.6	10.4
1500	1.8	no need	3.4	3.3	L2.4x2.4x1.3	7.2	4.4	L4.4x4.4x2.3	11.1	5.4	L6.5x6.5x3.4	15.1
2000	2.0	no need	4.6	3.7	L2.3x2.3x1.2	9.5	5.0	L4.2x4.2x2.2	14.6	6.0	L6.2x6.2x3.3	19.8
2500	2.2	no need	5.7	4.0	L2.2x2.2x1.1	11.8	5.4	L4.0x4.0x2.1	18.1	6.6	L5.9x5.9x3.1	24.5
3000	2.4	no need	6.9	4.3	L2.1x2.1x1.1	14.1	5.8	L3.8x3.8x2.0	21.6	7.1	L5.7x5.7x3.0	29.3
3500	2.5	no need	8.1	4.6	no need	16.5	6.2	L3.7x3.7x1.9	25.1	7.5	L5.5x5.5x2.9	34.0
4000	2.6	no need	9.2	4.8	no need	18.8	6.4	L3.5x3.5x1.8	28.7	7.9	L5.3x5.3x2.8	38.7
4500	2.7	no need	10.4	4.9	no need	21.2	6.7	L3.4x3.4x1.8	32.2	8.2	L5.1x5.1x2.7	43.5
5000	2.8	no need	11.6	5.1	no need	23.6	6.9	no need	35.8	8.5	L4.9x4.9x2.6	48.2
5500	----	----	----	5.2	no need	26.0	7.1	no need	39.4	8.8	L4.8x4.8x2.5	53.1
6000	----	----	----	5.3	no need	28.4	7.3	no need	43.0	9.0	L4.6x4.6x2.4	57.9
6500	----	----	----	5.5	no need	30.8	7.5	no need	46.7	9.2	L4.5x4.5x2.3	62.8
7000	----	----	----	5.5	no need	33.3	7.6	no need	50.4	9.4	no need	67.7
7500	----	----	----	5.6	no need	35.8	7.8	no need	54.1	9.6	no need	72.6
8000	----	----	----	5.7	no need	38.3	7.9	no need	57.8	9.8	no need	77.6
8500	----	----	----	5.8	no need	40.8	8.0	no need	61.6	9.9	no need	82.6
9000	----	----	----	5.8	no need	43.3	8.1	no need	65.4	10.1	no need	87.6
9500	----	----	----	5.9	no need	45.9	8.2	no need	69.2	10.2	no need	92.7
10000	----	----	----	6.0	no need	48.5	8.3	no need	73.1	10.3	no need	97.8
10500	----	----	----	----	----	----	8.4	no need	76.9	10.4	no need	103.0
11000	----	----	----	----	----	----	8.4	no need	80.9	10.5	no need	108.2
11500	----	----	----	----	----	----	8.5	no need	84.8	10.6	no need	113.4
12000	----	----	----	----	----	----	8.6	no need	88.8	10.7	no need	118.7

* The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values. Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

** Sections are calculated by assuming 3.5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).

*** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.

**** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.

***** Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.

Figure A. 3: Design table of post-tensioned glass T-beam for 3.5 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 3.5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Width (mm)											
	2500			3000			3500			4000		
	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	----	----	----	----	----	----	----	----	----	----	----	----
1500	6.2	L8.7x8.7x4.6	19.3	----	----	----	----	----	----	----	----	----
2000	7.0	L8.3x8.3x4.4	25.2	7.8	L10.5x10.5x5.5	30.7	----	----	----	----	----	----
2500	7.6	L8.0x8.0x4.2	31.1	8.5	L10.1x10.1x5.3	37.9	9.4	L12.3x12.3x6.5	44.7	----	----	----
3000	8.2	L7.7x7.7x4	37.1	9.2	L9.8x9.8x5.1	45.0	10.1	L11.9x11.9x6.3	53.1	11.0	L14.0x14.0x7.4	61.3
3500	8.7	L7.4x7.4x3.9	43.0	9.8	L9.4x9.4x5.0	52.1	10.8	L11.5x11.5x6.0	61.4	11.7	L13.6x13.6x7.2	70.9
4000	9.1	L7.2x7.2x3.8	48.9	10.3	L9.1x9.1x4.8	59.3	11.3	L11.1x11.1x5.9	69.8	12.3	L13.2x13.2x7.0	80.5
4500	9.5	L6.9x6.9x3.6	54.9	10.7	L8.8x8.8x4.7	66.5	11.8	L10.8x10.8x5.7	78.2	12.9	L12.9x12.9x6.8	90.1
5000	9.9	L6.7x6.7x3.5	60.9	11.2	L8.6x8.6x4.5	73.7	12.3	L10.5x10.5x5.5	86.6	13.4	L12.5x12.5x6.6	99.7
5500	10.2	L6.5x6.5x3.4	66.9	11.5	L8.3x8.3x4.4	80.9	12.7	L10.2x10.2x5.4	95.1	13.9	L12.2x12.2x6.4	109.4
6000	10.5	L6.3x6.3x3.3	72.9	11.9	L8.1x8.1x4.3	88.2	13.1	L10.0x10.0x5.3	103.5	14.3	L11.9x11.9x6.3	119.1
6500	10.8	L6.1x6.1x3.2	79.0	12.2	L7.9x7.9x4.2	95.5	13.5	L9.7x9.7x5.1	112.1	14.7	L11.6x11.6x6.1	128.9
7000	11.0	L6.0x6.0x3.1	85.1	12.5	L7.7x7.7x4.1	102.8	13.8	L9.5x9.5x5.0	120.7	15.1	L11.4x11.4x6.0	138.7
7500	11.3	L5.8x5.8x3.1	91.3	12.8	L7.5x7.5x4	110.2	14.2	L9.3x9.3x4.9	129.3	15.5	L11.1x11.1x5.9	148.5
8000	11.5	L5.7x5.7x3	97.5	13.0	L7.3x7.3x3.9	117.7	14.5	L9.1x9.1x4.8	138.0	15.8	L10.9x10.9x5.7	158.4
8500	11.7	no need	103.8	13.3	L7.2x7.2x3.8	125.1	14.7	L8.9x8.9x4.7	146.7	16.1	L10.7x10.7x5.6	168.4
9000	11.8	no need	110.1	13.5	L7.0x7.0x3.7	132.7	15.0	L8.7x8.7x4.6	155.5	16.4	L10.4x10.4x5.5	178.4
9500	12.0	no need	116.4	13.7	L6.8x6.8x3.6	140.3	15.2	L8.5x8.5x4.5	164.3	16.7	L10.2x10.2x5.4	188.5
10000	12.2	no need	122.8	13.9	L6.7x6.7x3.5	147.9	15.5	L8.3x8.3x4.4	173.2	16.9	L10.0x10.0x5.3	198.7
10500	12.3	no need	129.2	14.1	no need	155.6	15.7	L8.2x8.2x4.3	182.2	17.2	L9.9x9.9x5.2	208.9
11000	12.5	no need	135.7	14.2	no need	163.3	15.9	L8.0x8.0x4.2	191.2	17.4	L9.7x9.7x5.1	219.2
11500	12.6	no need	142.2	14.4	no need	171.1	16.1	L7.9x7.9x4.1	200.3	17.6	L9.5x9.5x5.0	229.5
12000	12.7	no need	148.7	14.5	no need	179.0	16.2	L7.7x7.7x4.1	209.4	17.8	L9.3x9.3x4.9	239.9

*** The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values.**
Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

**** Sections are calculated by assuming 3.5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).**

***** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.**

****** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.**

******* Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.**

Figure A. 4: Design table of post-tensioned glass T-beam for 3.5 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Distance between beams (mm): 500			1000			1500			2000		
	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	2.1	L1.4x1.4x0.7	3.4	3.7	L4.3x4.3x2.3	7.2	4.8	L7.6x7.6x4.0	11.2	5.7	L11.0x11.0x5.8	15.5
1500	2.5	L1.4x1.4x0.7	5.0	4.3	L4.1x4.1x2.2	10.5	5.6	L7.2x7.2x3.8	16.3	6.7	L10.4x10.4x5.5	22.3
2000	2.8	L1.3x1.3x0.7	6.6	4.8	L3.9x3.9x2.1	13.8	6.3	L6.8x6.8x3.6	21.3	7.6	L9.9x9.9x5.2	29.1
2500	3.1	no need	8.3	5.3	L3.7x3.7x2.0	17.1	6.9	L6.5x6.5x3.4	26.3	8.3	L9.5x9.5x5.0	35.8
3000	3.3	no need	9.9	5.6	L3.6x3.6x1.9	20.5	7.4	L6.3x6.3x3.3	31.4	8.9	L9.2x9.2x4.8	42.6
3500	3.5	no need	11.6	6.0	L3.4x3.4x1.8	23.8	7.9	L6.0x6.0x3.2	36.4	9.5	L8.9x8.9x4.7	49.4
4000	3.6	no need	13.3	6.2	L3.3x3.3x1.7	27.2	8.3	L5.8x5.8x3.1	41.5	10.0	L8.6x8.6x4.5	56.1
4500	3.8	no need	15.0	6.5	L3.1x3.1x1.7	30.5	8.6	L5.6x5.6x3.0	46.6	10.4	L8.3x8.3x4.4	62.9
5000	3.9	no need	16.6	6.7	no need	33.9	8.9	L5.4x5.4x2.9	51.7	10.8	L8.0x8.0x4.2	69.8
5500	----	----	----	6.9	no need	37.4	9.2	L5.2x5.2x2.8	56.8	11.2	L7.8x7.8x4.1	76.6
6000	----	----	----	7.1	no need	40.8	9.5	L5.1x5.1x2.7	62.0	11.5	L7.6x7.6x4.0	83.5
6500	----	----	----	7.2	no need	44.3	9.7	L4.9x4.9x2.6	67.2	11.8	L7.4x7.4x3.9	90.5
7000	----	----	----	7.4	no need	47.8	9.9	L4.8x4.8x2.5	72.4	12.1	L7.2x7.2x3.8	97.5
7500	----	----	----	7.5	no need	51.3	10.1	no need	77.7	12.4	L7.0x7.0x3.7	104.5
8000	----	----	----	7.6	no need	54.8	10.3	no need	83.0	12.6	L6.9x6.9x3.6	111.5
8500	----	----	----	7.7	no need	58.4	10.5	no need	88.3	12.8	L6.7x6.7x3.5	118.7
9000	----	----	----	7.8	no need	62.0	10.6	no need	93.7	13.0	L6.5x6.5x3.4	125.8
9500	----	----	----	7.9	no need	65.7	10.8	no need	99.1	13.2	L6.4x6.4x3.4	133.0
10000	----	----	----	8.0	no need	69.3	10.9	no need	104.6	13.4	no need	140.3
10500	----	----	----	----	----	----	11.0	no need	110.1	13.6	no need	147.6
11000	----	----	----	----	----	----	11.1	no need	115.7	13.8	no need	155.0
11500	----	----	----	----	----	----	11.2	no need	121.2	13.9	no need	162.4
12000	----	----	----	----	----	----	11.3	no need	126.9	14.1	no need	169.8

*** The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values.**
Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

**** Sections are calculated by assuming 5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).**

***** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.**

****** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.**

******* Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.**

Figure A. 5: Design table of post-tensioned glass T-beam for 5 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Width (mm) 2500: t (mm)	2500: Aluminum double angle (mm)	2500: Post tension (kN)	3000: t (mm)	3000: Aluminum double angle (mm)	3000: Post tension (kN)	3500: t (mm)	3500: Aluminum double angle (mm)	3500: Post tension (kN)	4000: t (mm)	4000: Aluminum double angle (mm)	4000: Post tension (kN)
1000	----	----	----	----	----	----	----	----	----	----	----	----
1500	7.6	L13.7x13.7x7.2	28.556	----	----	----	----	----	----	----	----	----
2000	8.6	L13.1x13.1x6.9	37.096	9.6226	L16.4x16.4x8.6	45.332	----	----	----	----	----	----
2500	9.5	L12.6x12.6x6.6	45.606	10.593	L15.8x15.8x8.3	55.607	11.586	L19.1x19.1x10.1	65.8333	----	----	----
3000	10.3	L12.2x12.2x6.4	54.1	11.4	L15.3x15.3x8.1	65.9	12.5	L18.5x18.5x9.7	77.9	13.5	L21.8x21.8x11.5	90.1
3500	10.9	L11.8x11.8x6.2	62.6	12.2	L14.9x14.9x7.8	76.1	13.4	L18.0x18.0x9.5	89.9	14.5	L21.2x21.2x11.2	103.9
4000	11.5	L11.4x11.4x6	71.1	12.9	L14.4x14.4x7.6	86.4	14.1	L17.5x17.5x9.2	101.9	15.3	L20.6x20.6x10.9	117.6
4500	12.0	L11.1x11.1x5.9	79.6	13.5	L14.1x14.1x7.4	96.6	14.8	L17.1x17.1x9.0	113.9	16.0	L20.2x20.2x10.6	131.4
5000	12.5	L10.8x10.8x5.7	88.2	14.0	L13.7x13.7x7.2	107.0	15.4	L16.7x16.7x8.8	126.0	16.7	L19.7x19.7x10.4	145.3
5500	12.9	L10.5x10.5x5.5	96.8	14.5	L13.4x13.4x7	117.3	16.0	L16.3x16.3x8.6	138.1	17.4	L19.3x19.3x10.1	159.1
6000	13.3	L10.3x10.3x5.4	105.4	15.0	L13.0x13.0x6.9	127.7	16.5	L15.9x15.9x8.4	150.2	17.9	L18.9x18.9x9.9	173.0
6500	13.7	L10.0x10.0x5.3	114.1	15.4	L12.7x12.7x6.7	138.1	17.0	L15.6x15.6x8.2	162.4	18.5	L18.5x18.5x9.7	187.0
7000	14.1	L9.8x9.8x5.1	122.9	15.8	L12.5x12.5x6.6	148.6	17.5	L15.3x15.3x8.0	174.6	19.0	L18.1x18.1x9.5	201.0
7500	14.4	L9.6x9.6x5.0	131.6	16.2	L12.2x12.2x6.4	159.1	17.9	L15.0x15.0x7.9	186.9	19.5	L17.8x17.8x9.4	215.1
8000	14.7	L9.3x9.3x4.9	140.5	16.6	L12.0x12.0x6.3	169.7	18.3	L14.7x14.7x7.7	199.3	19.9	L17.5x17.5x9.2	229.2
8500	15.0	L9.1x9.1x4.8	149.3	16.9	L11.7x11.7x6.2	180.4	18.7	L14.4x14.4x7.6	211.7	20.4	L17.2x17.2x9	243.4
9000	15.2	L8.9x8.9x4.7	158.3	17.2	L11.5x11.5x6.0	191.1	19.0	L14.1x14.1x7.4	224.2	20.8	L16.9x16.9x8.9	257.7
9500	15.5	L8.8x8.8x4.6	167.3	17.5	L11.3x11.3x5.9	201.9	19.4	L13.9x13.9x7.3	236.8	21.1	L16.6x16.6x8.7	272.0
10000	15.7	L8.6x8.6x4.5	176.3	17.8	L11.1x11.1x5.8	212.7	19.7	L13.6x13.6x7.2	249.4	21.5	L16.3x16.3x8.6	286.5
10500	15.9	L8.4x8.4x4.4	185.4	18.0	L10.9x10.9x5.7	223.6	20.0	L13.4x13.4x7.1	262.1	21.8	L16.0x16.0x8.4	301.0
11000	16.1	L8.3x8.3x4.3	194.6	18.3	L10.7x10.7x5.6	234.6	20.3	L13.2x13.2x6.9	274.9	22.2	L15.8x15.8x8.3	315.6
11500	16.3	L8.1x8.1x4.3	203.8	18.5	L10.5x10.5x5.5	245.6	20.6	L13.0x13.0x6.8	287.8	22.5	L15.5x15.5x8.2	330.2
12000	16.5	L8.0x8.0x4.2	213.1	18.7	L10.3x10.3x5.4	256.8	20.8	L12.8x12.8x6.7	300.7	22.8	L15.3x15.3x8.1	345.0

* The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values. Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

** Sections are calculated by assuming 5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).

*** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.

**** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.

***** Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.

Figure A. 6: Design table of post-tensioned glass T-beam for 5 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 7.5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Distance between beams (mm)											
	500			1000			1500			2000		
	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)	t (mm)	Aluminum double angle (mm)	Post tension (kN)
1000	3.0	L2.8x2.8x1.5	5.2	4.8	L7.6x7.6x4.0	11.2	6.1	L12.7x12.7x6.7	17.7	7.2	L18x18x9.5	24.6
1500	3.5	L2.7x2.7x1.4	7.7	5.6	L7.2x7.2x3.8	16.2	7.2	L12.0x12.0x6.3	25.4	8.5	L17.1x17.1x9	35.0
2000	3.9	L2.6x2.6x1.3	10.2	6.3	L6.8x6.8x3.6	21.3	8.1	L11.5x11.5x6.1	33.0	9.6	L16.4x16.4x8.6	45.2
2500	4.3	L2.4x2.4x1.3	12.6	6.9	L6.5x6.5x3.4	26.3	8.9	L11.1x11.1x5.8	40.6	10.6	L15.8x15.8x8.3	55.5
3000	4.6	L2.3x2.3x1.2	15.1	7.4	L6.3x6.3x3.3	31.3	9.6	L10.7x10.7x5.6	48.2	11.5	L15.3x15.3x8.1	65.7
3500	4.8	no need	17.6	7.9	L6.0x6.0x3.2	36.3	10.2	L10.3x10.3x5.4	55.8	12.2	L14.9x14.9x7.8	75.9
4000	5.0	no need	20.1	8.3	L5.8x5.8x3.1	41.4	10.8	L10.0x10.0x5.3	63.4	12.9	L14.5x14.5x7.6	86.2
4500	5.2	no need	22.6	8.6	L5.6x5.6x3.0	46.4	11.3	L9.7x9.7x5.1	71.1	13.5	L14.1x14.1x7.4	96.4
5000	5.4	no need	25.2	8.9	L5.4x5.4x2.9	51.5	11.7	L9.4x9.4x5.0	78.8	14.0	L13.7x13.7x7.2	106.7
5500	----	----	----	9.2	L5.3x5.3x2.8	56.7	12.1	L9.2x9.2x4.8	86.5	14.6	L13.4x13.4x7	117.0
6000	----	----	----	9.5	L5.1x5.1x2.7	61.8	12.5	L8.9x8.9x4.7	94.2	15.0	L13.1x13.1x6.9	127.4
6500	----	----	----	9.7	L4.9x4.9x2.6	67.0	12.8	L8.7x8.7x4.6	102.0	15.5	L12.8x12.8x6.7	137.8
7000	----	----	----	9.9	L4.8x4.8x2.5	72.2	13.1	L8.5x8.5x4.5	109.9	15.9	L12.5x12.5x6.6	148.3
7500	----	----	----	10.1	no need	77.5	13.4	L8.3x8.3x4.4	117.7	16.2	L12.2x12.2x6.4	158.8
8000	----	----	----	10.3	no need	82.8	13.7	L8.1x8.1x4.3	125.7	16.6	L12.0x12.0x6.3	169.4
8500	----	----	----	10.5	no need	88.1	13.9	L7.9x7.9x4.2	133.7	16.9	L11.7x11.7x6.2	180.0
9000	----	----	----	10.6	no need	93.5	14.2	L7.7x7.7x4.1	141.7	17.2	L11.5x11.5x6.1	190.7
9500	----	----	----	10.8	no need	98.9	14.4	L7.6x7.6x4.0	149.8	17.5	L11.3x11.3x5.9	201.4
10000	----	----	----	10.9	no need	104.4	14.6	L7.4x7.4x3.9	157.9	17.8	L11.1x11.1x5.8	212.2
10500	----	----	----	----	----	----	14.8	L7.3x7.3x3.8	166.1	18.1	L10.9x10.9x5.7	223.1
11000	----	----	----	----	----	----	15.0	no need	174.3	18.3	L10.7x10.7x5.6	234.1
11500	----	----	----	----	----	----	15.2	no need	182.6	18.6	L10.5x10.5x5.5	245.1
12000	----	----	----	----	----	----	15.3	no need	191.0	18.8	L10.3x10.3x5.4	256.2

*** The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values.**
Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.

**** Sections are calculated by assuming 7.5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).**

***** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.**

****** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.**

******* Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.**

Figure A. 7: Design table of post-tensioned glass T-beam for 7.5 kN/m^2 load

Design Tables for Post-Tensioned Glass T-Beams

[Table for 7.5 kN/m^2 distributed load] - Web thickness (mm)/Minimum aluminum dimensions (Type 6063-T6)/Post-tension (kN)

Length (mm) - Beam depth=Length/10	Width (mm) 2500: t (mm)	2500: Aluminum double angle (mm)	2500: Post tension (kN)	3000: t (mm)	3000: Aluminum double angle (mm)	3000: Post tension (kN)	3500: t (mm)	3500: Aluminum double angle (mm)	3500: Post tension (kN)	4000: t (mm)	4000: Aluminum double angle (mm)	4000: Post tension (kN)
1000	----	----	----	----	----	----	----	----	----	----	----	----
1500	9.6	L22.3x22.3x11.7	45.0	----	----	----	----	----	----	----	----	----
2000	11.0	L21.5x21.5x11.3	58.0	12.1	L26.6x26.6x14.0	71.1	----	----	----	----	----	----
2500	12.1	L20.8x20.8x10.9	70.9	13.4	L25.8x25.8x13.6	86.8	14.6	L30.9x30.9x16.3	103.1	----	----	----
3000	13.1	L20.2x20.2x10.6	83.8	14.5	L25.1x25.1x13.2	102.3	15.8	L30.1x30.1x15.9	121.3	17.0	L35.2x35.2x18.5	140.8
3500	13.9	L19.6x19.6x10.3	96.6	15.5	L24.4x24.4x12.9	117.9	16.9	L29.4x29.4x15.5	139.6	18.2	L34.4x34.4x18.1	161.7
4000	14.7	L19.1x19.1x10.0	109.5	16.4	L23.9x23.9x12.6	133.4	17.9	L28.7x28.7x15.1	157.8	19.3	L33.7x33.7x17.7	182.6
4500	15.5	L18.6x18.6x9.8	122.4	17.2	L23.3x23.3x12.3	148.9	18.8	L28.1x28.1x14.8	176.0	20.3	L33x33x17.4	203.5
5000	16.1	L18.2x18.2x9.6	135.3	18.0	L22.8x22.8x12.0	164.5	19.7	L27.5x27.5x14.5	194.2	21.3	L32.4x32.4x17	224.4
5500	16.7	L17.8x17.8x9.4	148.2	18.7	L22.3x22.3x11.8	180.1	20.4	L27.0x27.0x14.2	212.4	22.1	L31.8x31.8x16.7	245.3
6000	17.3	L17.4x17.4x9.2	161.2	19.3	L21.9x21.9x11.5	195.7	21.2	L26.5x26.5x13.9	230.7	22.9	L31.2x31.2x16.4	266.3
6500	17.8	L17.0x17.0x9.0	174.3	19.9	L21.5x21.5x11.3	211.4	21.8	L26.0x26.0x13.7	249.1	23.7	L30.7x30.7x16.1	287.3
7000	18.3	L16.7x16.7x8.8	187.4	20.5	L21.1x21.1x11.1	227.1	22.5	L25.6x25.6x13.5	267.5	24.4	L30.2x30.2x15.9	308.4
7500	18.7	L16.4x16.4x8.6	200.5	21.0	L20.7x20.7x10.9	242.9	23.1	L25.2x25.2x13.2	286.0	25.0	L29.7x29.7x15.6	329.6
8000	19.2	L16.1x16.1x8.5	213.8	21.5	L20.3x20.3x10.7	258.8	23.6	L24.7x24.7x13.0	304.5	25.6	L29.3x29.3x15.4	350.8
8500	19.6	L15.8x15.8x8.3	227.0	22.0	L20.0x20.0x10.5	274.8	24.2	L24.4x24.4x12.8	323.2	26.2	L28.8x28.8x15.2	372.1
9000	19.9	L15.5x15.5x8.2	240.4	22.4	L19.7x19.7x10.4	290.8	24.7	L24.0x24.0x12.6	341.9	26.8	L28.4x28.4x14.9	393.5
9500	20.3	L15.2x15.2x8.0	253.8	22.8	L19.4x19.4x10.2	306.9	25.2	L23.6x23.6x12.4	360.7	27.3	L28.0x28.0x14.7	415.0
10000	20.6	L15.0x15.0x7.9	267.3	23.2	L19.1x19.1x10.0	323.1	25.6	L23.3x23.3x12.3	379.6	27.8	L27.6x27.6x14.5	436.6
10500	21.0	L14.7x14.7x7.8	280.9	23.6	L18.8x18.8x9.9	339.4	26.0	L22.9x22.9x12.1	398.5	28.3	L27.2x27.2x14.3	458.3
11000	21.3	L14.5x14.5x7.6	294.6	24.0	L18.5x18.5x9.7	355.8	26.5	L22.6x22.6x11.9	417.6	28.8	L26.9x26.9x14.1	480.1
11500	21.6	L14.3x14.3x7.5	308.3	24.3	L18.2x18.2x9.6	372.2	26.8	L22.3x22.3x11.7	436.8	29.2	L26.5x26.5x14.0	502.0
12000	21.8	L14.0x14.0x7.4	322.1	24.6	L18.0x18.0x9.4	388.8	27.2	L22.0x22.0x11.6	456.1	29.6	L26.2x26.2x13.8	524.0

*** The values and sections provided in this table is for reference only. Engineers should check and verify before using these suggested values. Additional stability, strength, servicibility, long term performance checks might be necessary. Glue allowable strength is taken as 5 MPa.**

**** Sections are calculated by assuming 7.5 kN/m^2 distrbuted load + dead load (Load factor=1.0; Factor of Safety=3.0, Allowable Stress Design).**

***** The compressive strength of glass is taken as 400 MPa and tensile strength for both transfer and final cases is taken as 30 MPa considering float glass.**

****** The post tensioning cord. distance from the bottom of T-beam is assumed as 2.5 times the web thickness. Flange thickness = Web thickness.**

******* Aluminum L sections are calculated as minimum values and may not be available in the market; FS=2 is used and closest larger size may be used.**

Figure A. 8: Design table of post-tensioned glass T-beam for 7.5 kN/m^2 load

B. ADDITIONAL FINITE ELEMENT MODEL RESULTS

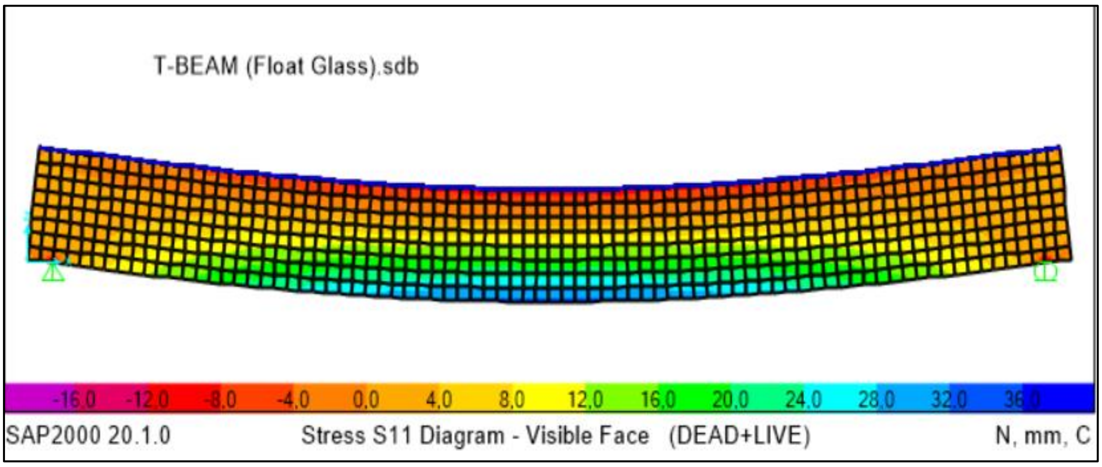

Figure B. 1: Stress at final case of float glass T-beam without post-tensioning

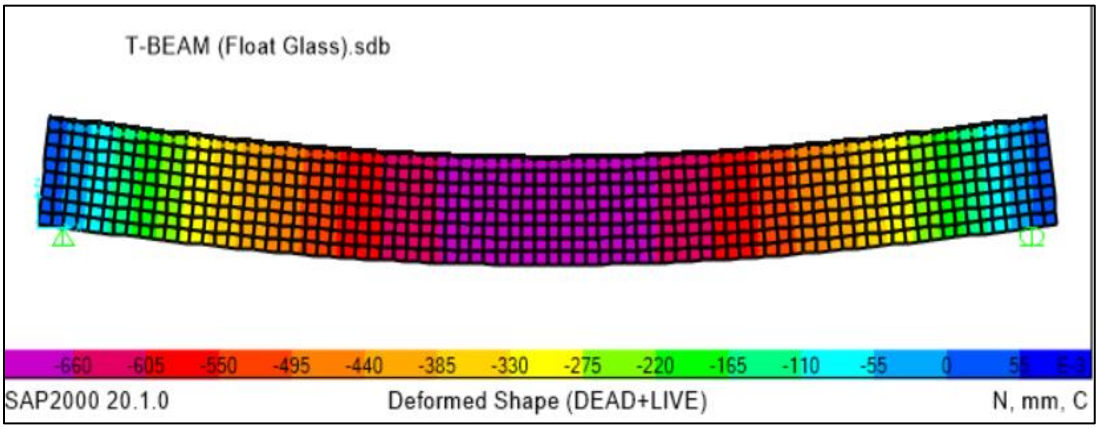

Figure B. 2: Deflection at final case of float glass T-beam without post-tensioning

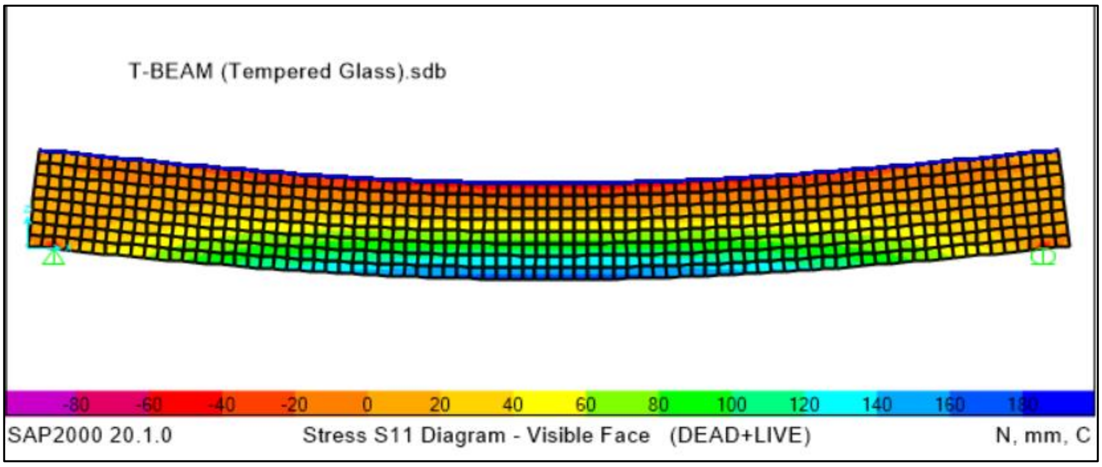

Figure B. 3: Stress at final case of tempered glass T-beam without post-tensioning

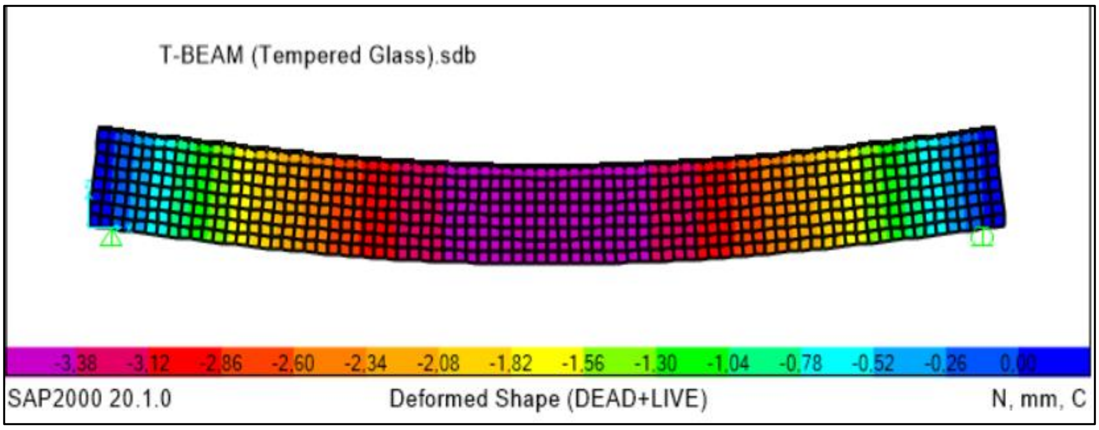

Figure B. 4: Defl. at final case of tempered glass T-beam without post-tensioning

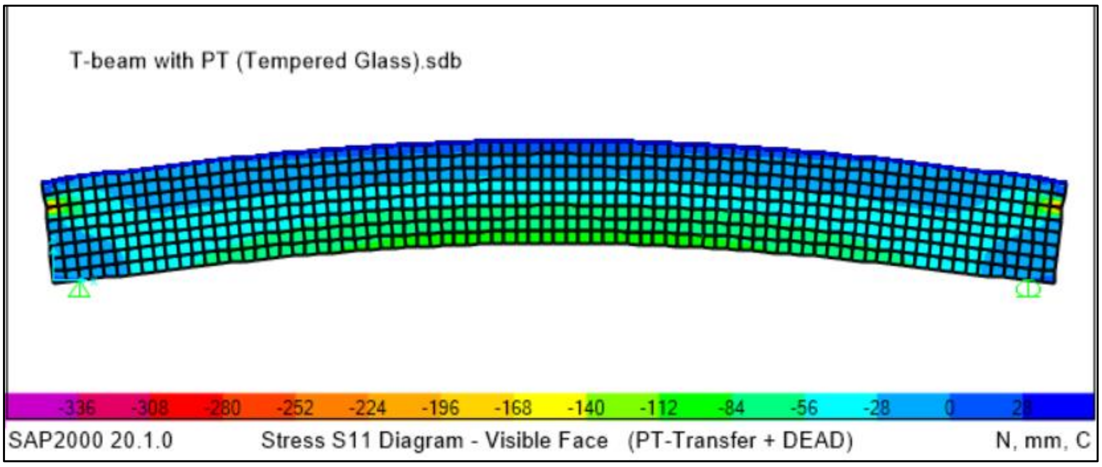

Figure B. 5: Stress at transfer case of post-tensioned tempered glass T-beam

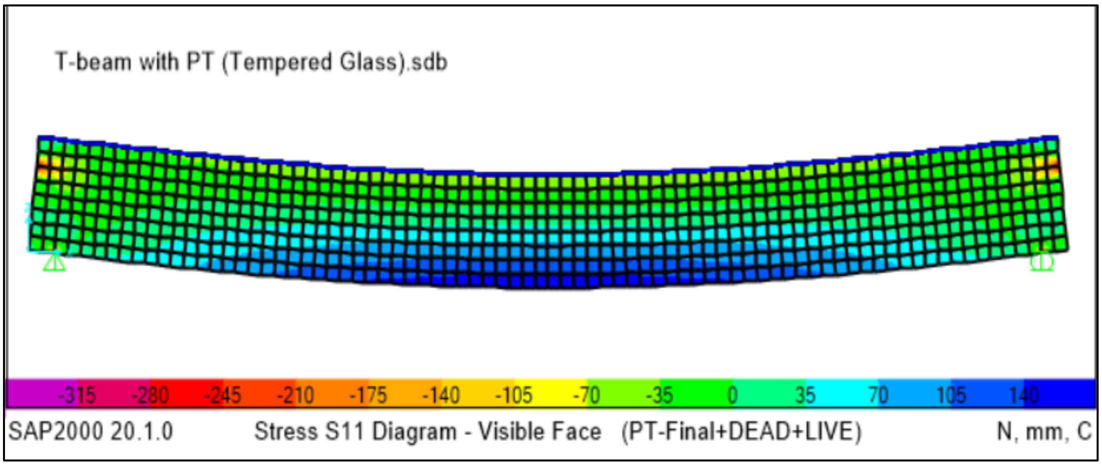

Figure B. 6: Stress at transfer case of post-tensioned tempered glass T-beam

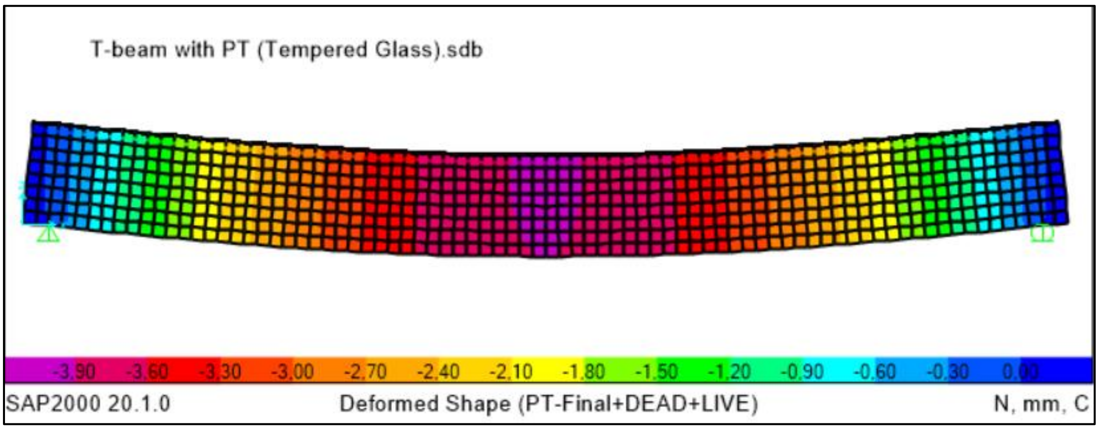

Figure B. 7: Deflection of post-tensioned tempered glass T-beam at final case